Multiplex, Inc.
Photonics for Communications

Highly Efficient RF Lightwave Integrated Transmitters

Contract DAAD17-01-C-0077

RFLICS PI Review

El Segundo, CA 7/31/01

Dr. Won T. Tsang (Dr. Randall Wilson – presenting)

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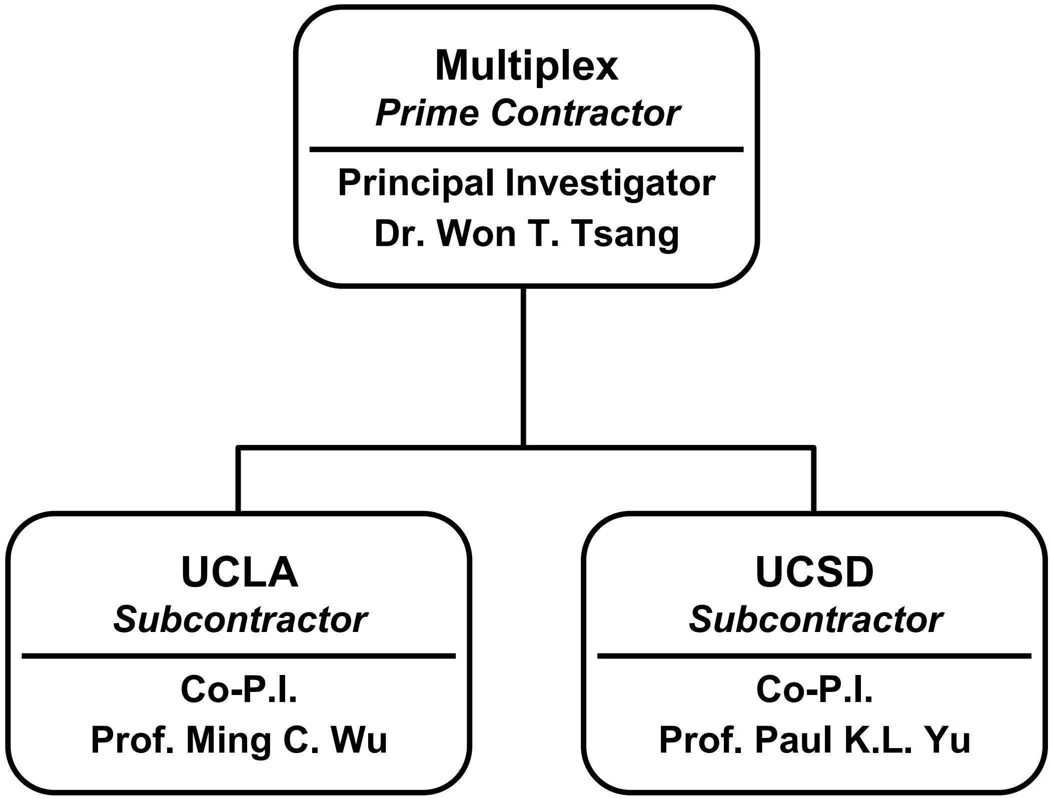
Team Management



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RFLICS Goals

Develop the key components for a RF-photonic link that meets the following specifications:

- Transmit/process RF signal in the 0.5-50GHz range
- Broadband (>40GHz)
- High spurious-free dynamic range (SFDR >100dB-Hz$^{2/3}$)
- Low loss or with RF gain (>-1dB)
- Monolithically integratable for low cost.

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Multiplex/UCLA/UCSD Program Goals

- **Traveling-Wave Electroabsorption-Modulated Laser Modules (TW-EML):**
  - Develop low-Vpi (<0.5V), broadband (>40GHz) traveling-wave semiconductor electroabsorption modulators (EAM).
  - Monolithically integrate with distributed feedback (DFB) lasers using selective-area growth (SAG) by metal organic chemical vapor deposition (MOCVD).

- **Optical Injection Locking of Gain-lever Laser Modules:**
  - Develop a RF-photonic transmitter link by combining strong optical injection locking with gain-lever modulation.
  - Enhance the direct modulation bandwidth to achieve >40GHz operation.
  - Improve the RF modulation efficiency by 20dB (link gain improved by 40dB).
  - Reduce relative intensity noise (RIN) of the laser by 10 to 20 dB by using strong optical injection locking.

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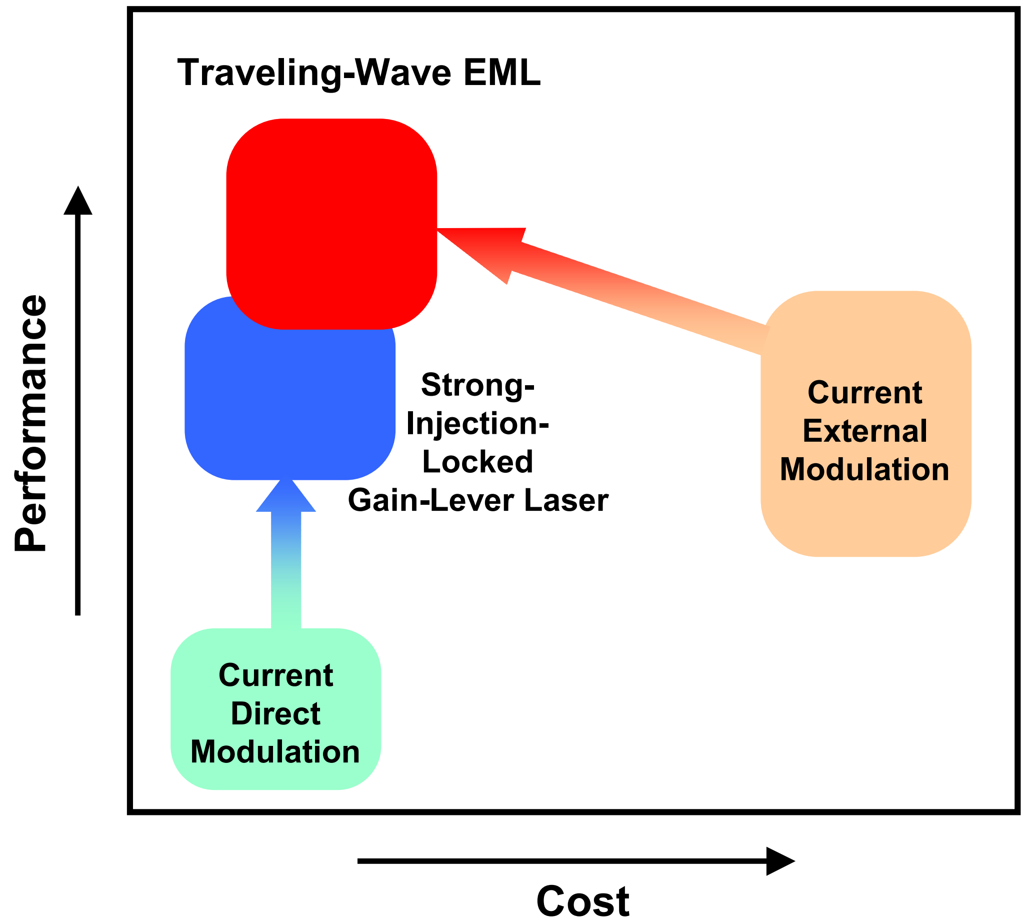
Objective of RF-Lightwave Integrated Transmitters (RFLIT)



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Program Roadmap

Federal Government Fiscal Year	FY'01			FY'02				FY'03				FY'04				FY'05				
Calendar Year	2001				2002				2003				2004				2005			
Task Name	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.0 Travelling Wave EML																				
1.1 EML on SI Substrate Development						◆	1													
1.2 Travelling Wave EML Development							◆	2												
1.3 Low Vpi Modulator Development								◆	3											
1.4 High Frequency Package Development										◆	4									
1.5 Traveling Wave-EML Link Characterization															◆	5		◆	6	
2.0 Optical Injection Locking of Gain-Lever Laser Dev.																				
2.1 Gain-Level DFB Laser Development					◆	7														
2.2 Tunable DFB Laser Development							◆	8												
2.3 Optical Injection Locking									◆	9										
2.4 Direct Modulation Laser Package Development										◆	10									
2.5 Direct Mod. Characterization with Strong Inj. Locking													◆	11				◆	12	

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Milestones and Deliverables

Milestone	Task	Milestone/Deliverable
1	1.1	Complete development of baseline EML technology on SI-InP
2	1.2	Complete development of 1st generation TW-EML
3	1.3	Complete development of 1st generation TW-EML with low Vpi
4	1.4	TW-EML high frequency package complete. Link characterization of 1st gen TW-EML complete. Deliver alpha prototype TW-EML
5	1.5	Link characterization of 2nd gen TW-EML complete. Deliver beta prototype TW-EML
6	1.5	Link characterization of 3rd gen TW-EML complete. Deliver final prototype TW-EML
7	2.1	Complete development of 1st generation Gain-Lever DFB
8	2.2	Complete development of 1st generation Tunable DFB
9	2.3	Package development for high frequency Gain-Lever laser complete
10	2.4	Optical injection locking experiment complete using 1st gen components from milestones 7 and 8.
11	2.5	Link characterization of optical injection locked Gain-Level DFB laser. Deliver beta prototype.
12	2.5	Link characterization of 2nd gen optical injection locked Gain-Lever DFB. Deliver final prototypes.

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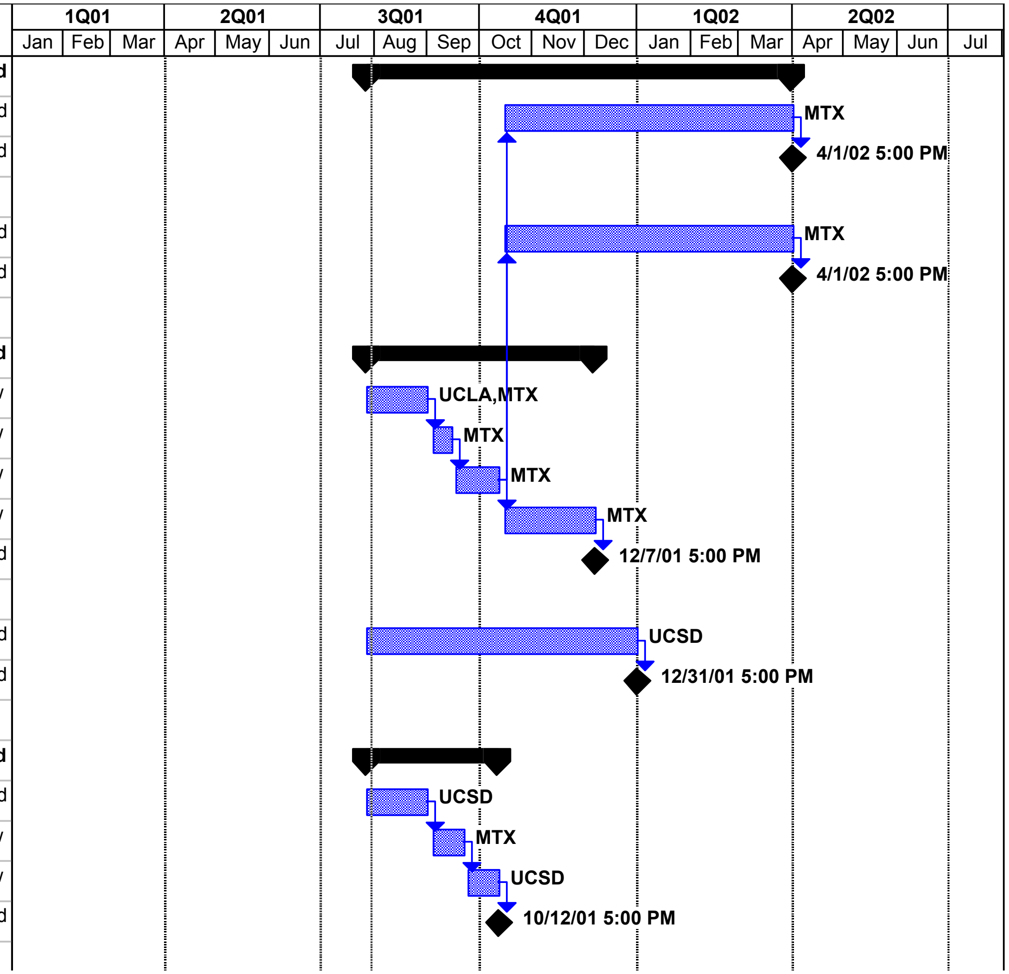
Task 1.1 Detailed Schedule/Milestones

ID	Task Name	Duration
1	**1.1 EML on SI Substrate**	**177d**
2	1.1.1 Baseline EML growth	121d
3	1.1.1 Complete	0d
4		
5	1.1.2 SAG and regrowth	121d
6	1.1.2 Complete	0d
7		
8	**1.1.3 fabrication process**	**96d**
9	Share structure/mask set info. Formulate process seq.	5.2w
10	Design mask set using autocad.	2w
11	procure mask levels from vendor	4w
12	Grow wafer, process wafer	8w
13	1.1.3 Complete	0d
14		
15	1.1.4 MOCVD growth approaches	112d
16	1.1.4 Complete	0d
17		
18	**1.1.5 Material loss characterization**	**56d**
19	Specification of test structure	26d
20	Calibration and growth to deliver 1 wafer	3w
21	Fab wafer and test	3w
22	1.1.5 Complete	0d
23		



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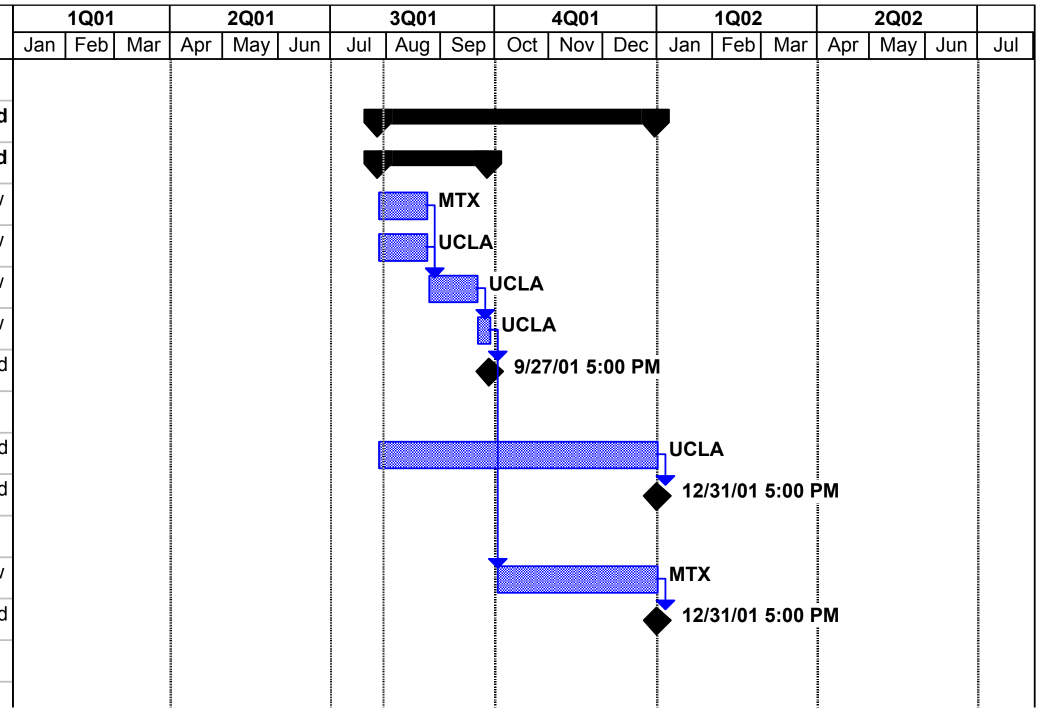
Task 2.1 Detailed Schedule/Milestones

ID	Task Name	Duration
23		
24	**2.1 Gain-Lever DFB Laser Development**	**112d**
25	**2.1.1 Initial prototype development**	**45d**
26	Calibrate and grow wafers	4w
27	Design mask	4w
28	Fab wafer	4w
29	Test device	1w
30	2.1.1 Complete	0d
31		
32	2.1.2 Modeling of design and select optimum	112d
33	2.1.2 Complete	0d
34		
35	2.1.3 Develop manufacturing process for selected design	13w
36	2.1.3 Complete	0d
37		
38		



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Most Significant Accomplishment

- Contract Awarded June 6, 2001
- Traveling Wave Electro-Optical Models at both UCLA and UCSD are operational and are producing favorable results and predictions ready to be compared with experiment.

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RFLIT: Electroabsorption Modulator for Broadband Access

Paul Yu -UCSD

A. Is there traveling-wave effect in short device?

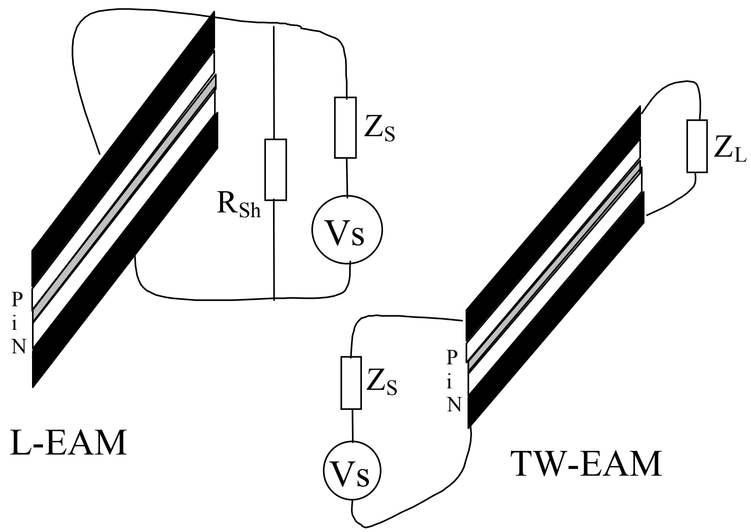
Traveling wave model
How the traveling-wave model migrates to lumped-element model
How to break the RC-bandwidth-limit rule by TW-EAM design

B. The design and performance of TW-EAM devices fabricated at UCSD

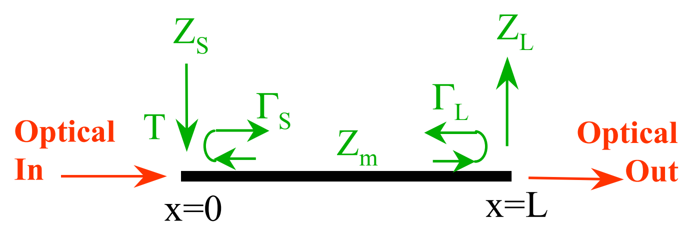
Device structure
Microwave properties of the waveguide
Modulation frequency response and bandwidth
Optical saturation power

C. Current Investigation

Electrical Connections of L-EAM and TW-EAM



To achieve maximum link RF gain,
the best waveguide length has been ~ 200 μm
for both L-EAM and TW-EAM.
(limited by optical propagation loss)



Both are ~ 200 μm long.

$$\Gamma_S = \frac{Z_S - Z_m}{Z_S + Z_m} \qquad \Gamma_L = \frac{Z_L - Z_m}{Z_L + Z_m} \qquad T = \frac{2Z_m}{Z_S + Z_m} = 1 - \Gamma_S$$

Are there any advantages for the electrical connection to TW-EAM ?

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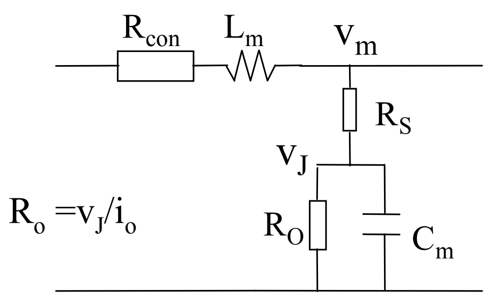
Circuit Model for TW-EAM

Small-segment lumped-element circuit model for TW-EAM transmission line.



$$Z_{series} = R_{con} + j\omega L_m$$

$$Z_{shunt} = R_S + \frac{R_O}{1 + j\omega R_O C_m}$$

$$Z_m = \sqrt{Z_{series} Z_{shunt}} \qquad \gamma_\mu = \alpha_\mu + j\beta_\mu = \sqrt{\frac{Z_{series}}{Z_{shunt}}}$$

Modified TW-EAM frequency response :

$$M'(f) = M(f)\left|\frac{Z_{junc}}{Z_{shunt}}\right|^2 \qquad Z_{junc} = \frac{R_O}{1 + j\omega R_O C_m}$$

From TW-EAM to L-EAM

$$M(f)=\left|\frac{T}{e^{\gamma_\mu L}-\Gamma_L\Gamma_S e^{-\gamma_\mu L}}\left\{\frac{e^{j\beta_o L}-e^{\gamma_\mu L}}{(j\beta_o-\gamma_\mu)L}+\Gamma_L\frac{e^{j\beta_o L}-e^{-\gamma_\mu L}}{(j\beta_o+\gamma_\mu)L}\right\}\times\frac{Z_{junc}}{Z_{shunt}}\right|^2$$

For L-EAM:
Γ_L=1,
L is very short.

$$=\left|\frac{T}{e^{\gamma_\mu L}-\Gamma_S e^{-\gamma_\mu L}}\{1+1\}\times\frac{Z_{junc}}{Z_{shunt}}\right|^2=\left|\frac{2(1-\Gamma_S)}{(1-\Gamma_S)+\gamma_\mu L(1+\Gamma_S)}\times\frac{Z_{junc}}{Z_{shunt}}\right|^2$$

$T=1-\Gamma_S$

$$=\left|\frac{2Z_{junc}}{Z_{shunt}+LZ_S}\right|^2$$

$$\frac{1+\Gamma_S}{1-\Gamma_S}=\frac{Z_s}{Z_m}\qquad\frac{\gamma_\mu}{Z_m}=\frac{1}{Z_{shunt}}$$

$$=\left|\frac{2}{1+j\omega C_m L(Z_S+R_S/L)}\right|^2$$

Assume $Z_{junc}=\dfrac{1}{j\omega C_m}$ $\quad Z_{shunt}=R_S+\dfrac{1}{j\omega C_m}$

1). L-EAM means both short-length and open-termination,
2). Proper termination for short TW-EAM could break RC-limit rule for bandwidth,
3). Velocity-matching is not very important.

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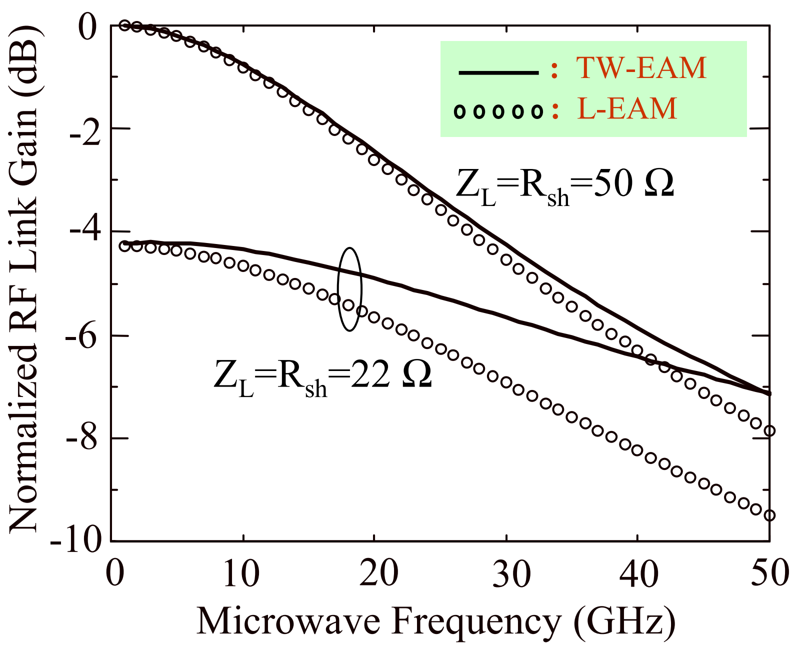
Breaking the RC-Limit Rule for Modulation Bandwidth

Comparing L-EAM and TW-EAM with the same optical waveguides:

L=0.2mm, L_m= 0.5 nH/mm, C_m=1.2 pF/mm, R_{con}=3.5 Ω-mm^{-1}GHz$^{-1/2}$, R_S=1 Ω-mm, R_O=10^6 Ω-mm, n_o=3.5



3-dB bandwidth:

	Z_L=R_{sh}=50 Ω	Z_L=R_{sh}=22 Ω
L-EAM	20 GHz	30 GHz
TW-EAM	21 GHz	50 GHz

Low impedance termination for TW-EAM can break the RC-limit rule for bandwidth

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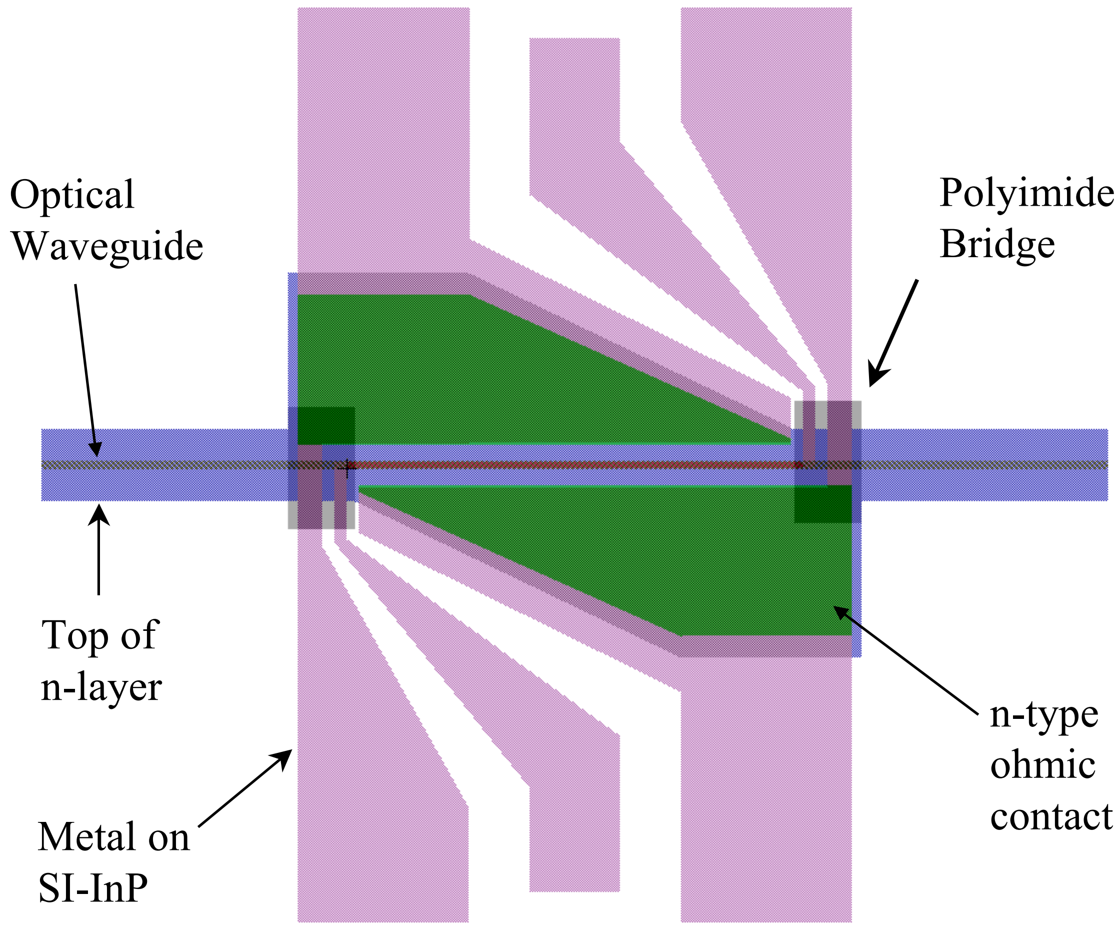
Device Top View



Device Design: Cross-section

FKE device with <u>large optical cavity</u>

w and d are determined for <u>maximum modulation efficiency</u>.

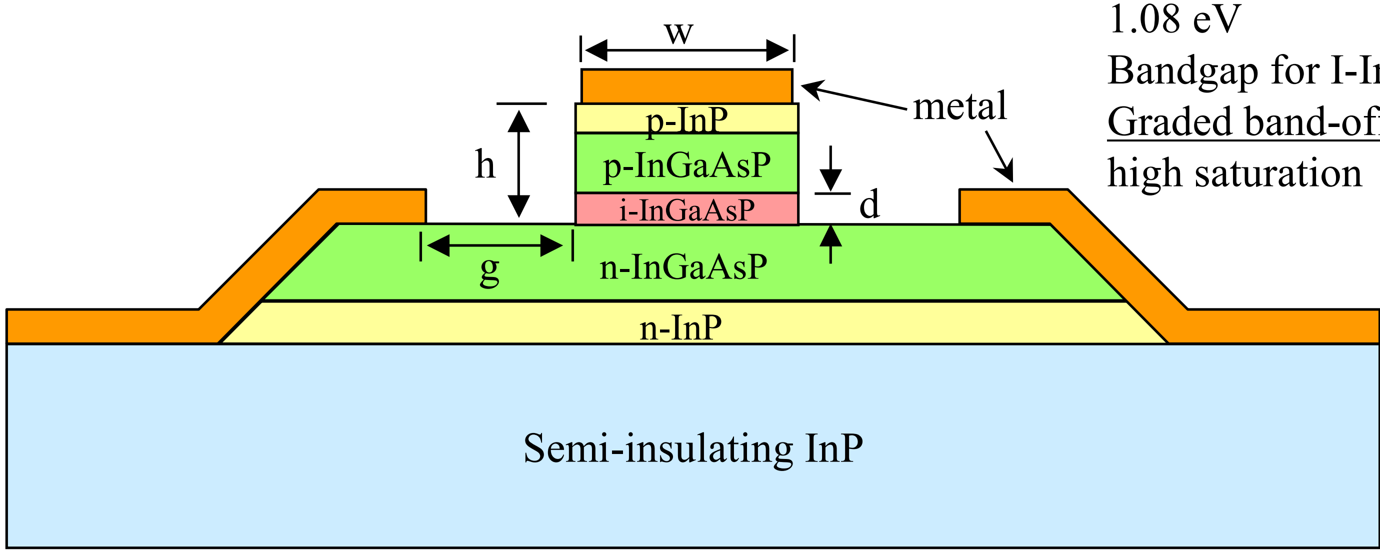
w~ 3 μm, d~0.35 μm
g~5-10 μm, h~2 μm

Larger L_m — w — smaller R_{con}

smaller R_S — g — Larger L_m

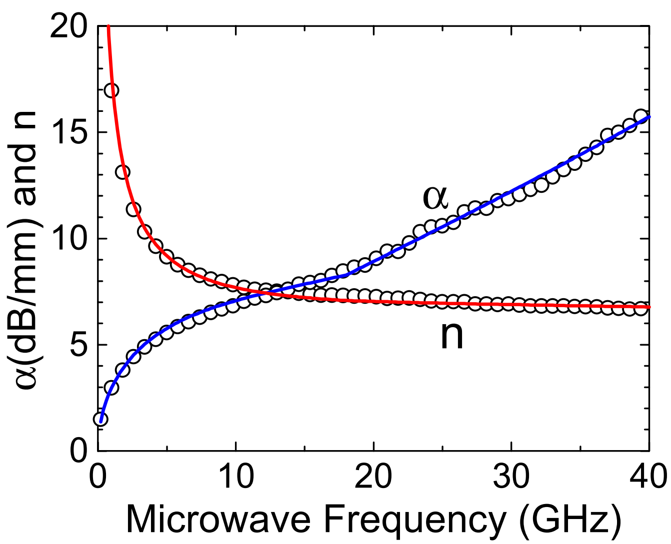
smaller R_S — h — Larger L_m

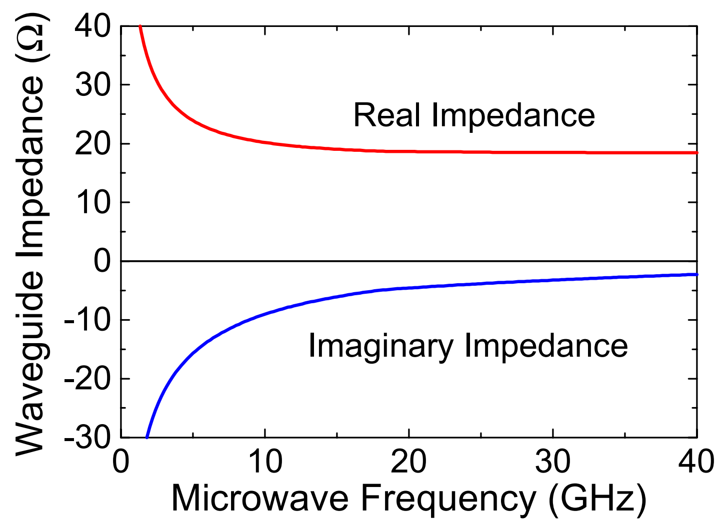
Bandgap for p- and n-InGaAsP: 1.08 eV
Bandgap for I-InGaAsP: 1.00 eV
<u>Graded band-offset</u> is good for high saturation



Waveguide Microwave Properties

For the fabricated TW-EAM device



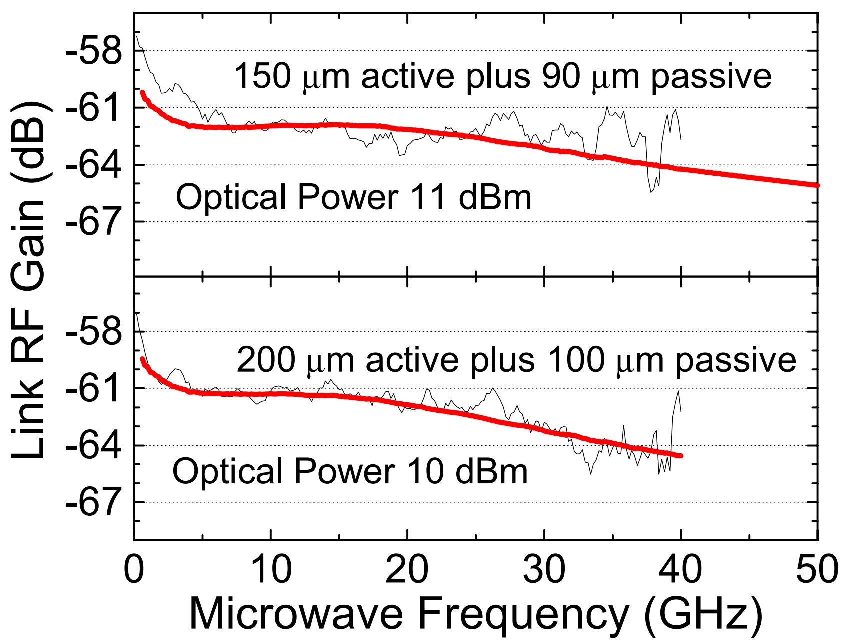


De-embedded circuit parameters from curves of α(f) and n(f) :

L_m~ 0.40 nH/mm, C_m~1.3 pF/mm, R_{con}~7.3 Ω-mm^{-1}-GHz$^{-1/2}$, R_S~0.58 Ω-mm.

Device Frequency Response

Termination impedance 26.2 Ω. Detector RF responsivity ~0.12 A/W up to 40 GHz.



For 200 μm long L-EAM with the same optical waveguide:

C_m~1.3*0.2= 0.26 pF, R_S~0.58/0.2 =3 Ω, R_{Sh}=26.2 Ω
Assume 0.03 pF capacitance due to bonding pad.
Modulation bandwidth ~ 25 GHz

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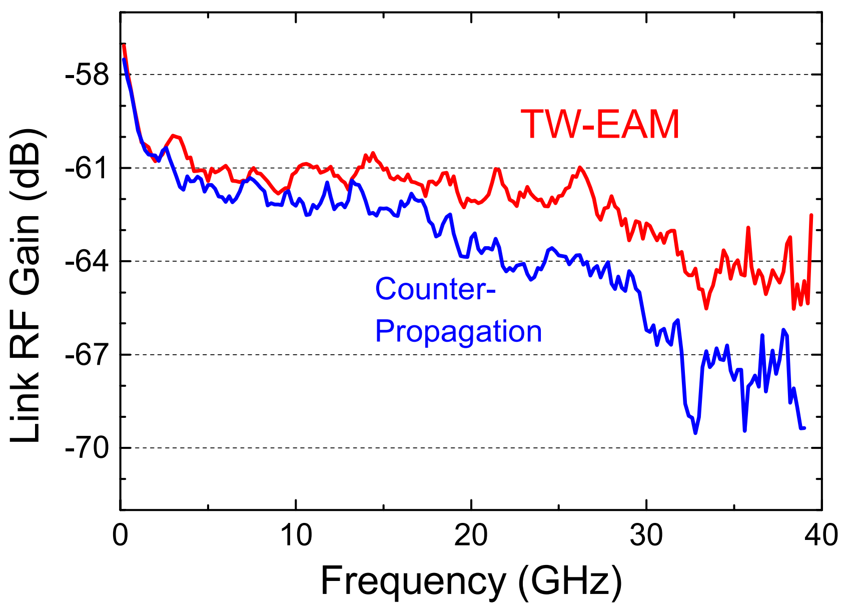
Counter-Propagation Measurement



200 μm long active length
plus 100 μm long passive length

Input optical power: 11.5 dBm

Detector RF responsivity:
~0.20 A/W up to 40 GHz

Modulator optical loss: 11.5 dB

From 5 GHz, 3-dB cut-off :
at 25 GHz for blue curve
at 36 GHz for red curve

$$M(f) = \left| \frac{T}{e^{\gamma_\mu L} - \Gamma_L \Gamma_S e^{-\gamma_\mu L}} \left\{ \frac{e^{j\beta_o L} - e^{\gamma_\mu L}}{(j\beta_o - \gamma_\mu)L} + \Gamma_L \frac{e^{j\beta_o L} - e^{-\gamma_\mu L}}{(j\beta_o + \gamma_\mu)L} \right\} \times \frac{Z_{junc}}{Z_{shunt}} \right|^2$$

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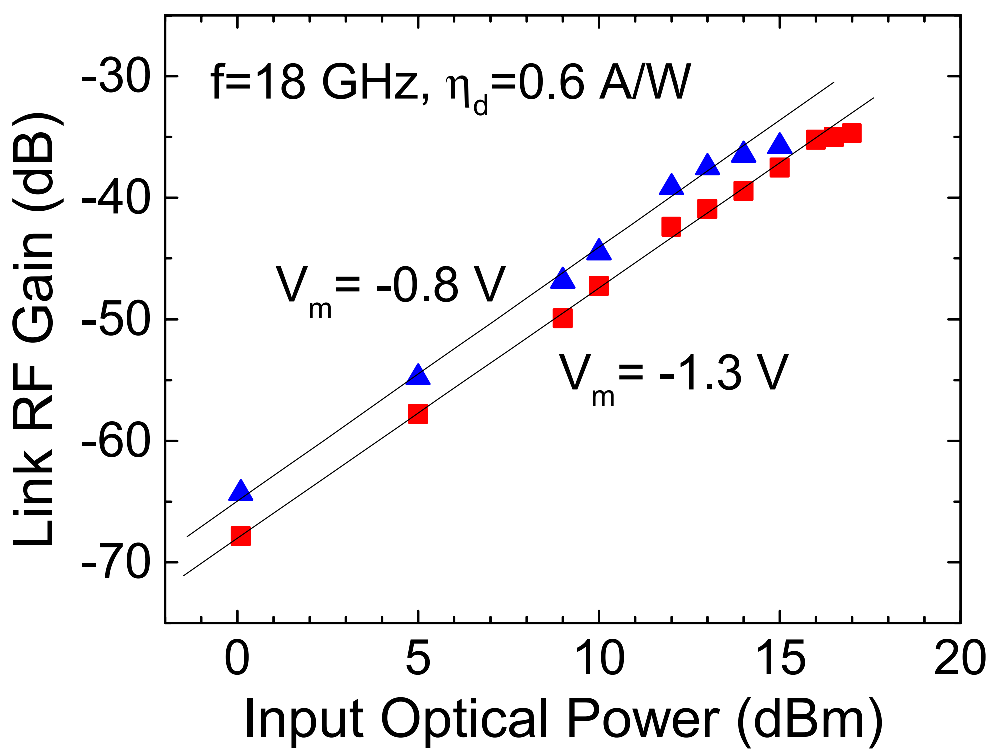
Optical Saturation Measurement

Two devices shown:
200 μm long modulation length
plus 100 μm long passive section.

26.2 Ω termination.

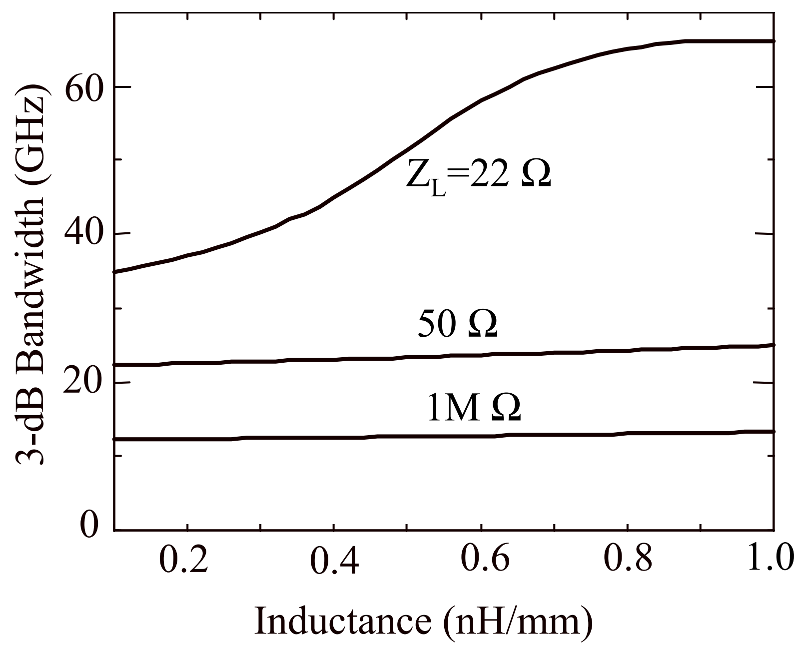
optical saturation power @
1-dB gain compression point:

25 mW and 45 mW respectively

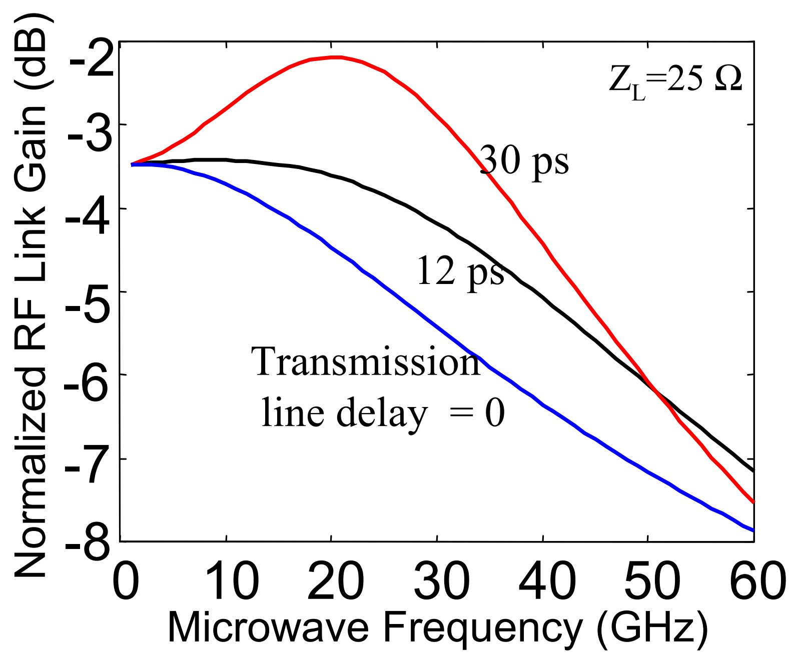


Current Investigations for TW-EAM with Larger Bandwidth

a. Increasing Waveguide Inductance



b. Design Terminator Transmission Line



Inductance is <1 nH/mm for an usual TW-EAM.

Summary

1. Traveling-wave design can improve performance for short device.

2. Low impedance termination for TW-EAM can break the RC-limit rule for the bandwidth.

3. The fabricated TW-EAM devices show good performance.
   bandwidth> 40 GHz,
   optical saturation power~45 mW.

4. Current Investigation underway for low V_{π}, large bandwidth EA modulator design for
   Traveling wave EML.

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RF Lightwave Integrated Circuits (R-FLICS) PI Meeting
July 31, 2001

Highly Efficient RF Lightwave Integrated Transmitters (RFLIT)

Ming C. Wu, UCLA

Graduate Students:
Sagi Mathai, Juthika Basak, Tom Jung, Erwin Lau

Collaboration:
Federica Cappelluti, Prof. Giovanni Ghione
Politecnico di Torino, Italy

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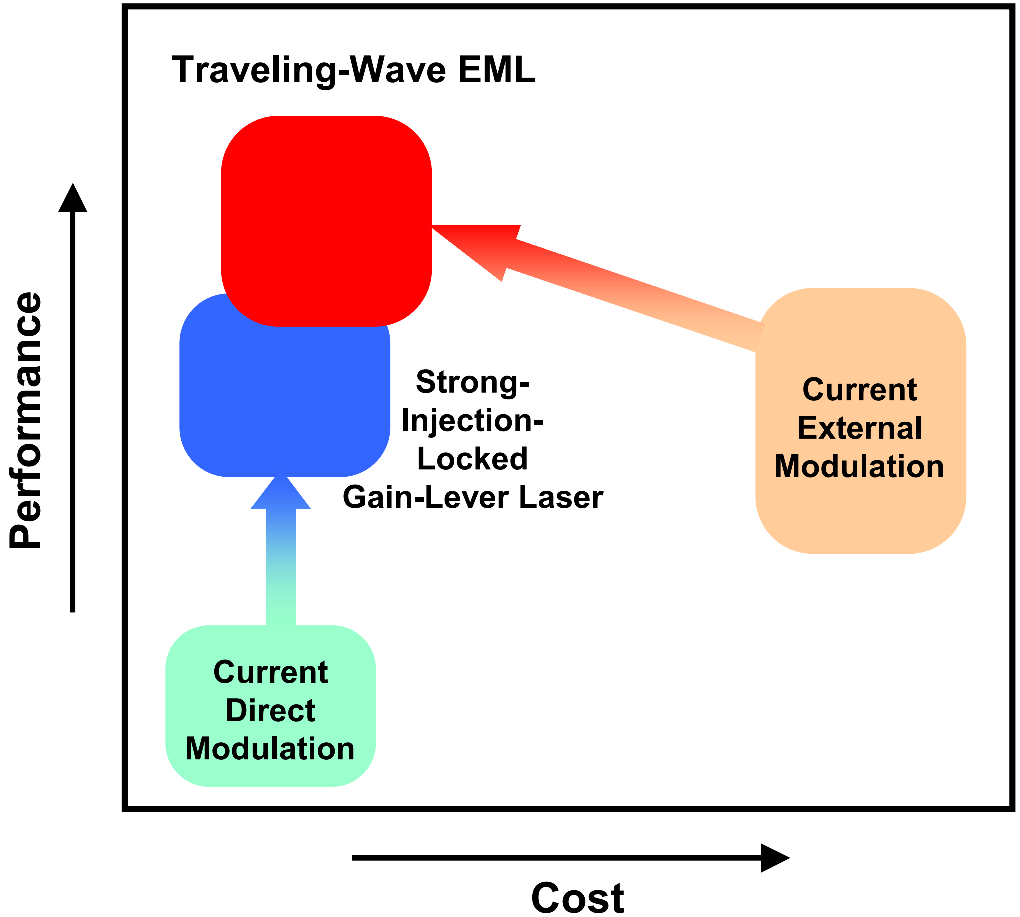
Objective of RF-Lightwave Integrated Transmitters (RFLIT)



Program Goals

- Team Goal:
  - Develop chip-scale RF Lightwave Integrated Transmitters (RFLIT) for high performance military and commercial RF systems:
- UCLA Goal:
  - Traveling-wave EML:
    - Design and modeling of EML
    - Assist in fabrication of prototype EML
  - Directly modulation with strong optical injection locking
    - Enhance bandwidth with strong optical injection locking
    - Enhance efficiency with split-contact (gain-lever) modulation
    - Comprehensive modeling
    - Fabrication and experimental demonstration

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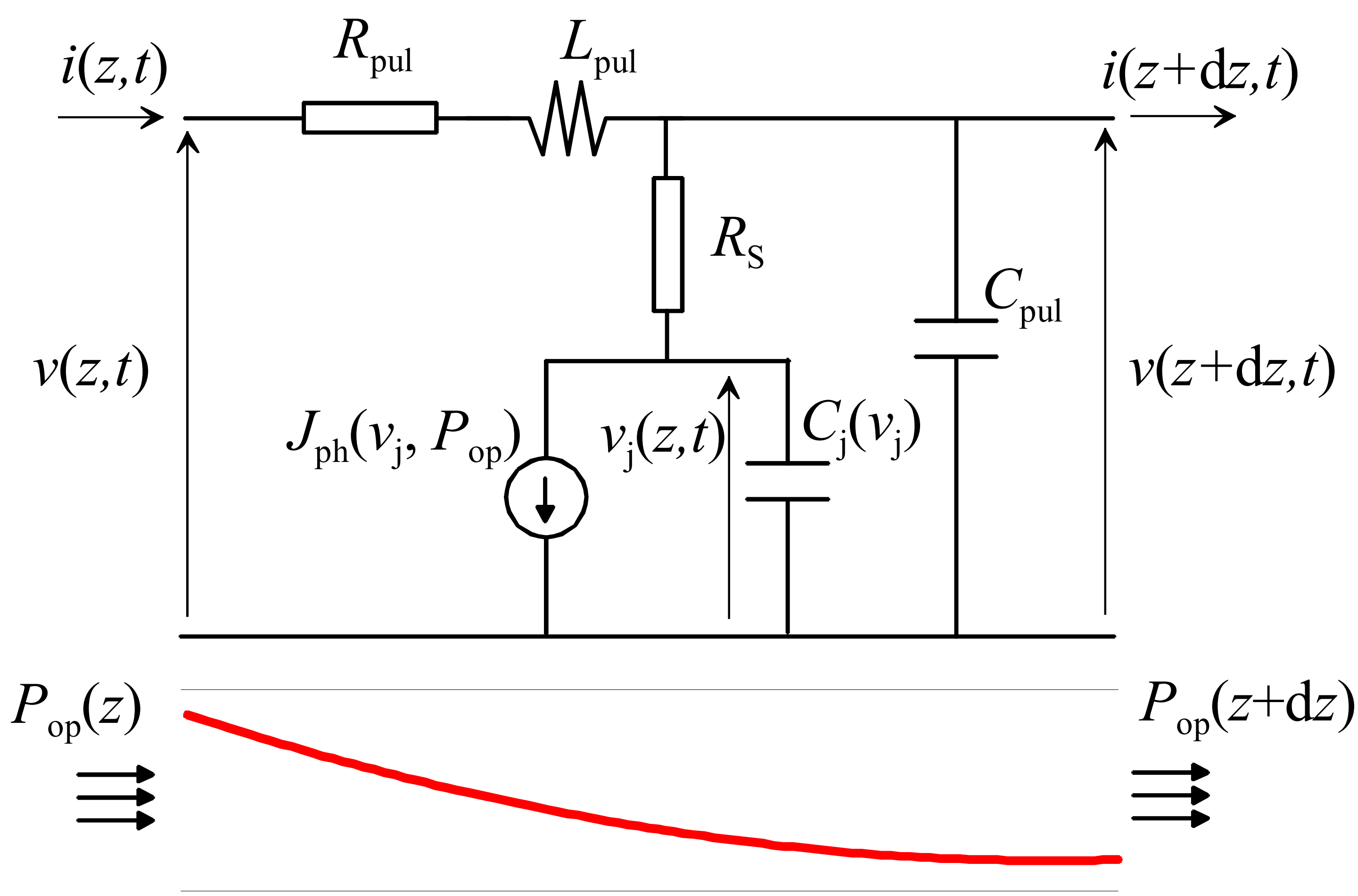
Self-Consistent Time-Domain Large Signal of TW-EAMs

- TW-EAMs models proposed so far are derived in quasi-static conditions and exploit linear approximations of microwave and optical parameters.
- Several nonlinear effects take place in TW-EAMs:
  - Absorption is a nonlinear function of applied voltage
  - Photocurrent causes non-uniform microwave losses and saturates at high optical power
  - Propagation characteristics of the microwave electrodes depend on the applied voltage through the photocurrent and, to a lesser extent, through the nonlinear junction capacitance
- Frequency-domain linear models cannot account for the RF and optical power induced nonlinear behavior, even at a small signal level

The Dynamic TW-EAM Model (I)

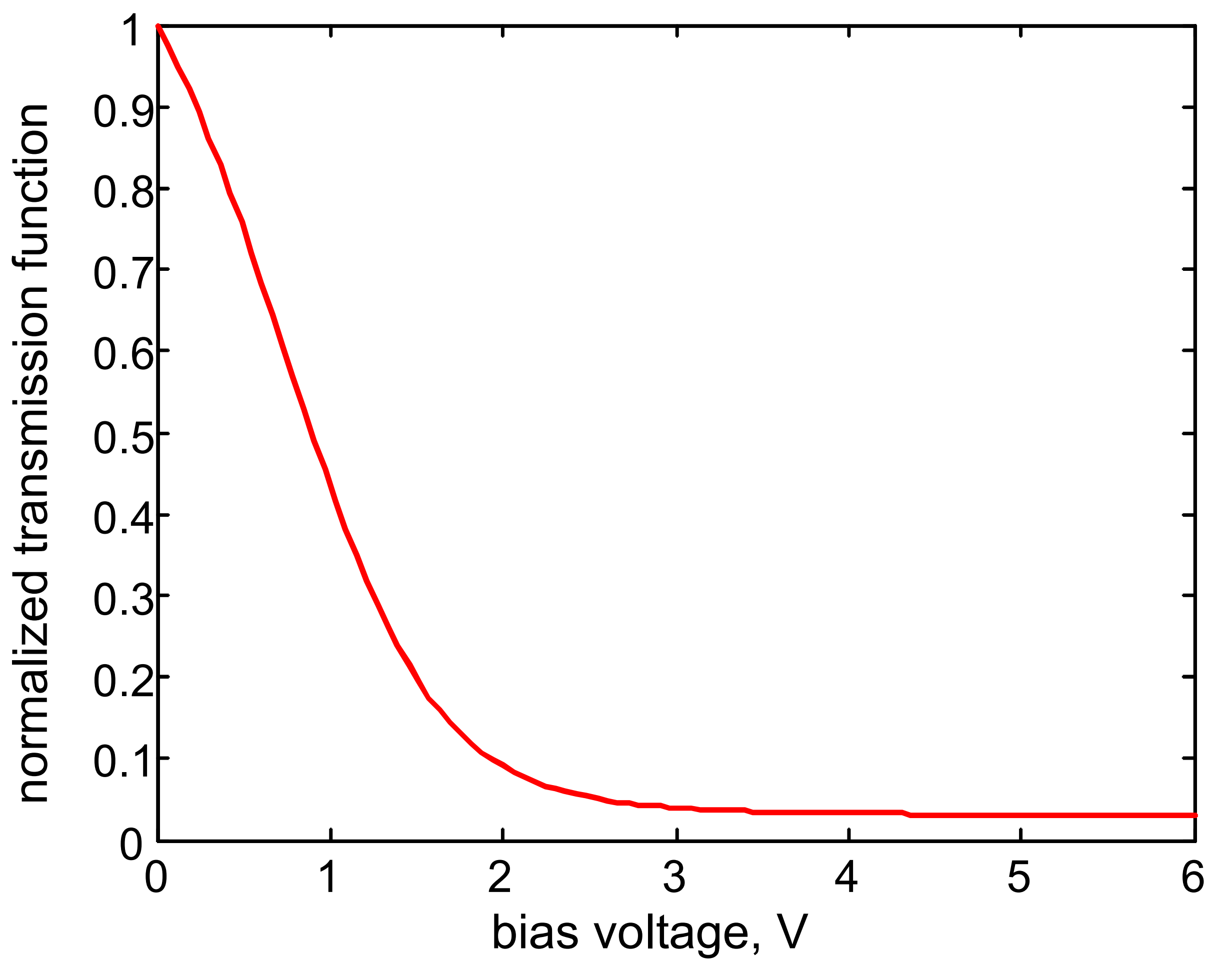


The Dynamic TW-EAM Model (II)

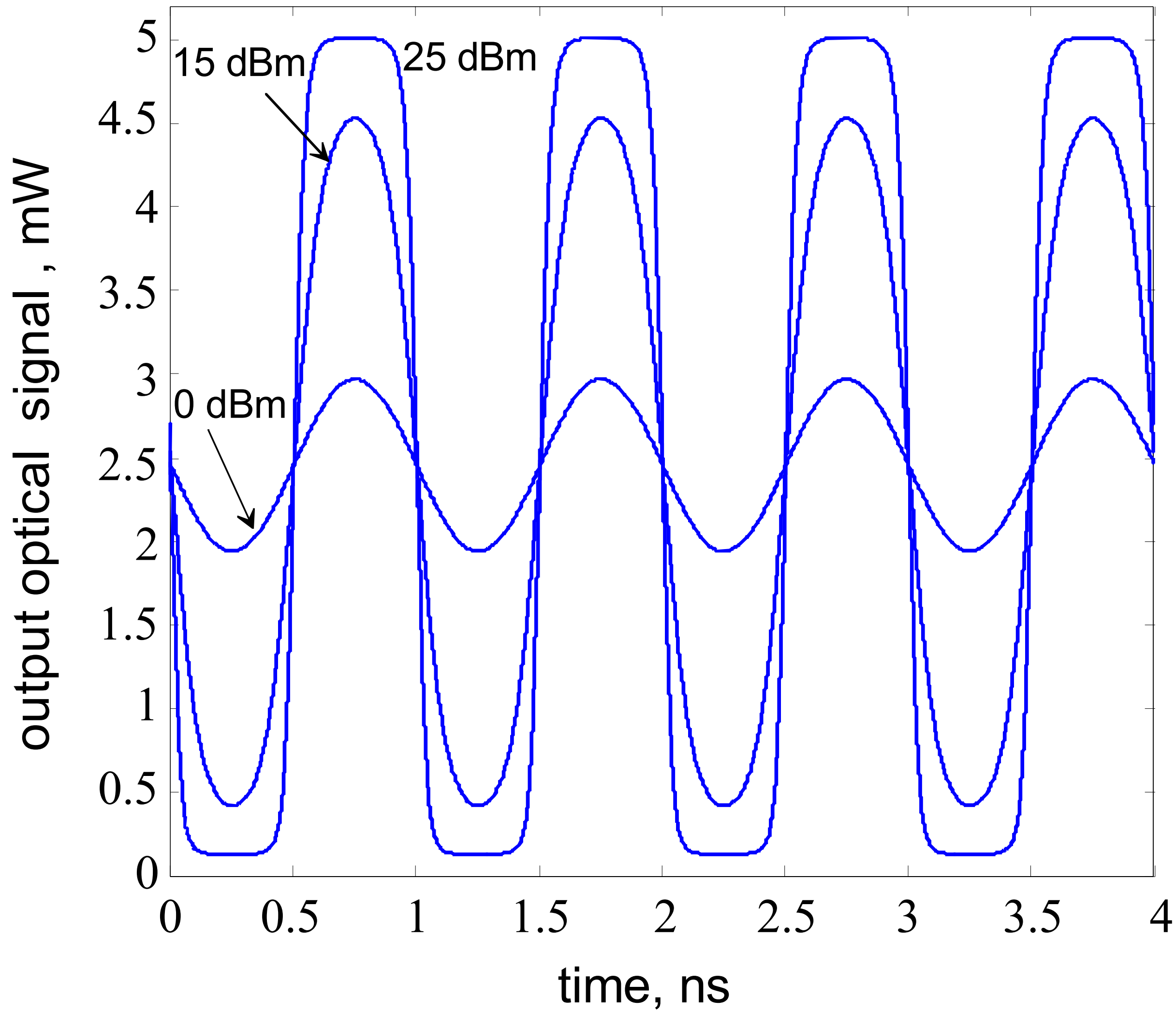
- Microwave and optical fields propagation equations coupled through:
  - voltage and optical power dependence of the photogenerated current
  - microwave losses induced from the photogenerated current
- Empirical formulas were used for the voltage and optical power dependence of the absorption
- Coupled equations implemented in the time domain
- Numerical solution of the equations obtained following a first order finite difference approach
- System solved self-consistently through a semi-implicit method

Results

- **Simulations performed on a 200 μm long EAM:**



Time Domain Optical Waveforms



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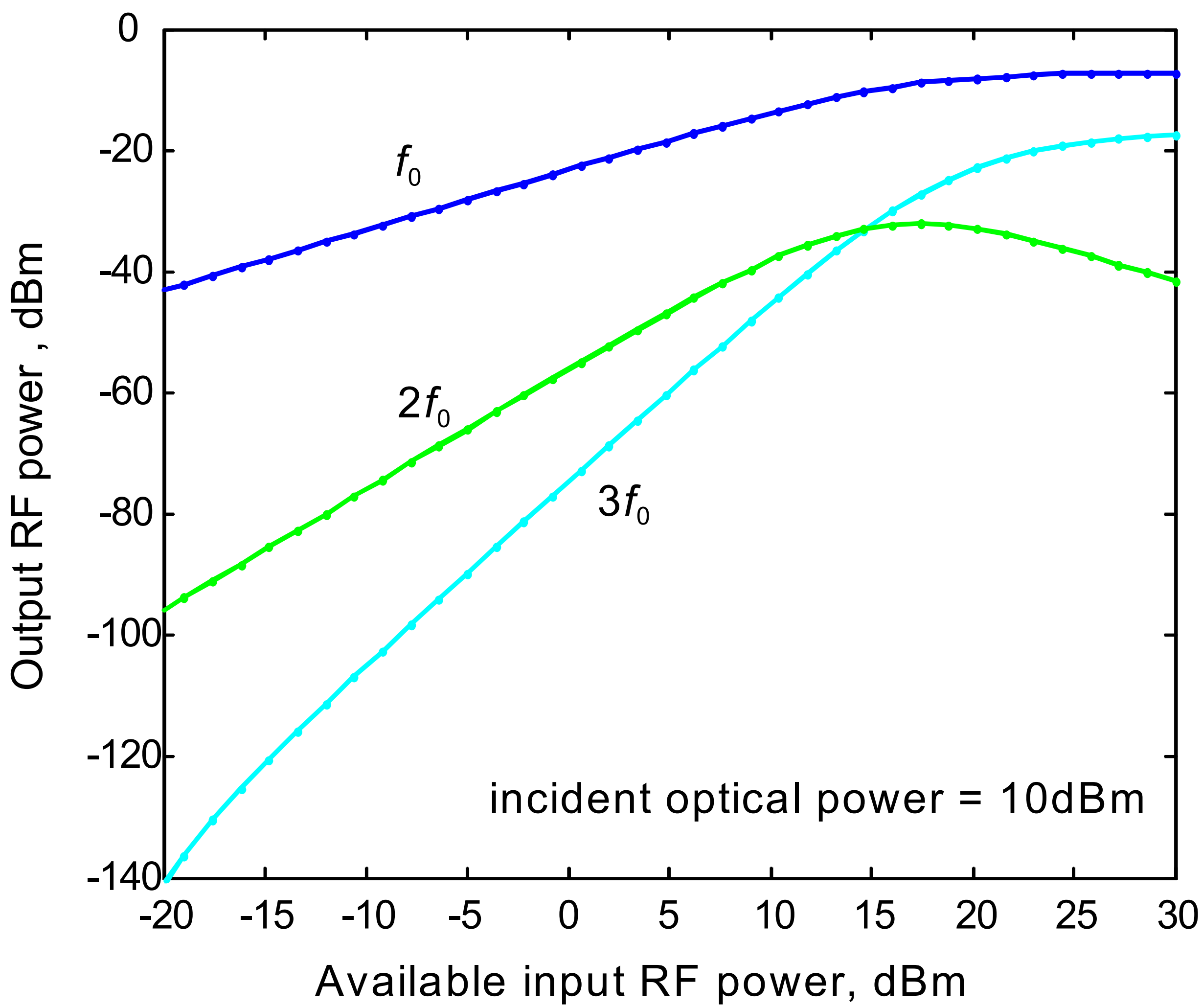
Saturation and Nonlinear Distortions



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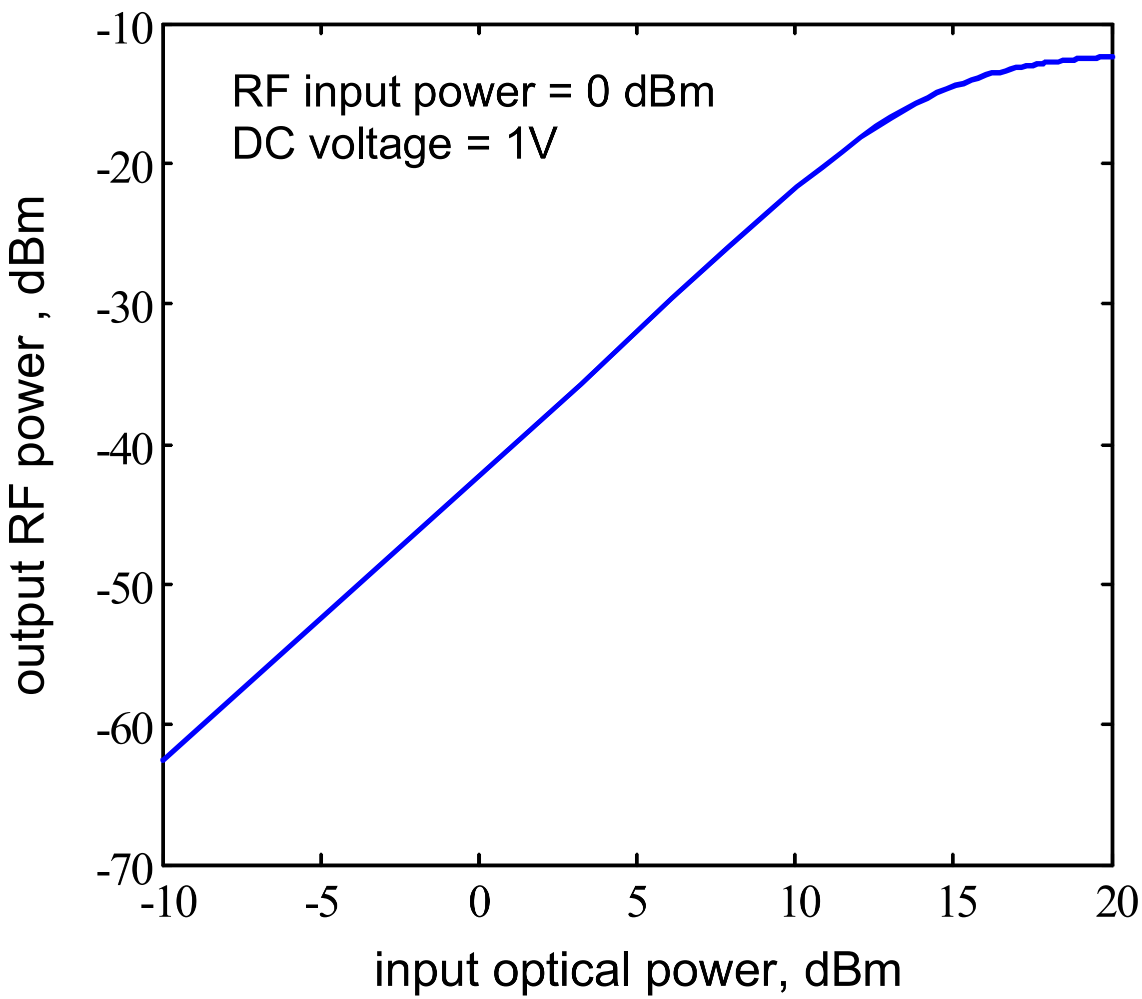
Optical Power Induced Saturation



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Directly Modulated RF Lightwave Transmitters

- Direct modulation of semiconductor laser
  → Compact, simple, low cost
- Disadvantages of direct modulation:
  - Low optical-RF conversion efficiency
  - Bandwidth limited by relaxation oscillation frequency
  - Large nonlinear distortion
  - Chirp
  - High RIN
- Has been primarily used in low performance systems

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Directly Modulated Laser with Strong Optical Injection Locking

- Strong optical injection locking significantly enhance the performance of direct modulation:
  - Increase the modulation bandwidth to beyond the fundamental limit of relaxation oscillation
  - Reduce nonlinear distortions
  - Reduce RIN
  - Reduce chirp
- Enhance the modulation efficiency using gain-lever effect

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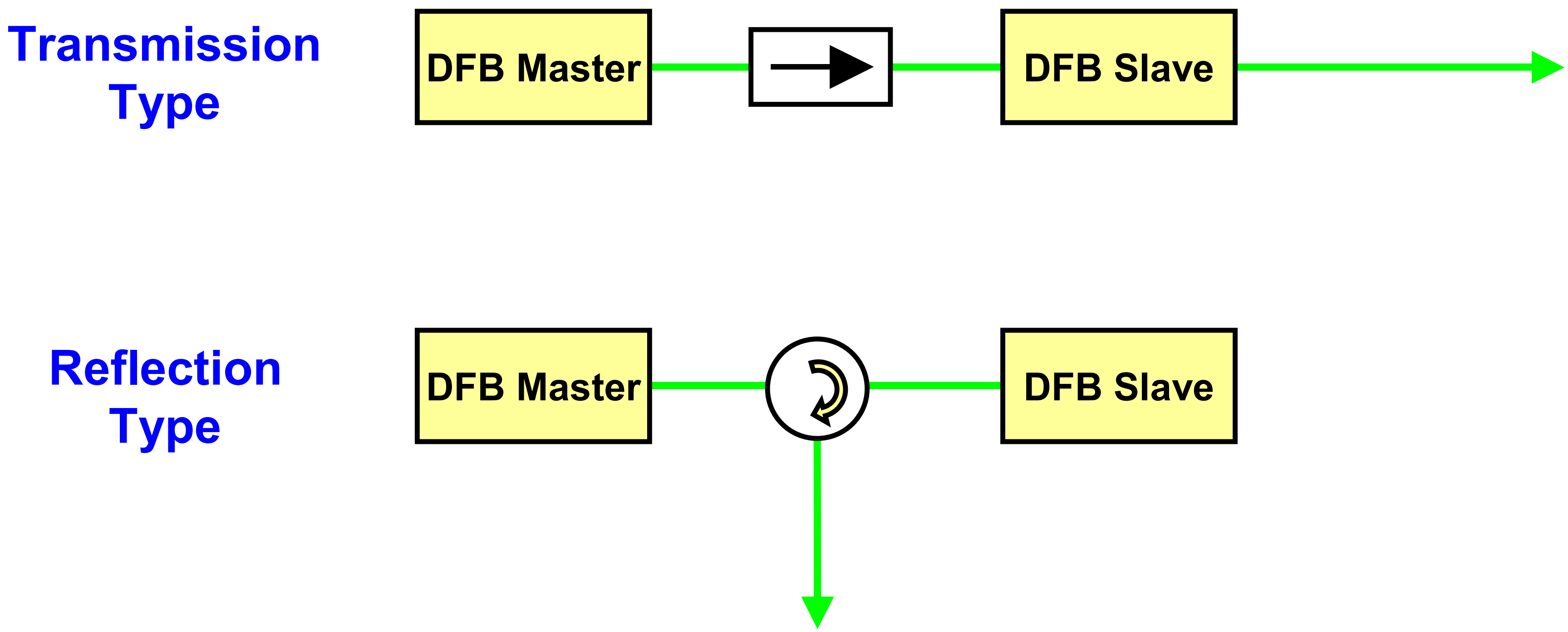
Injection Locking Set-up



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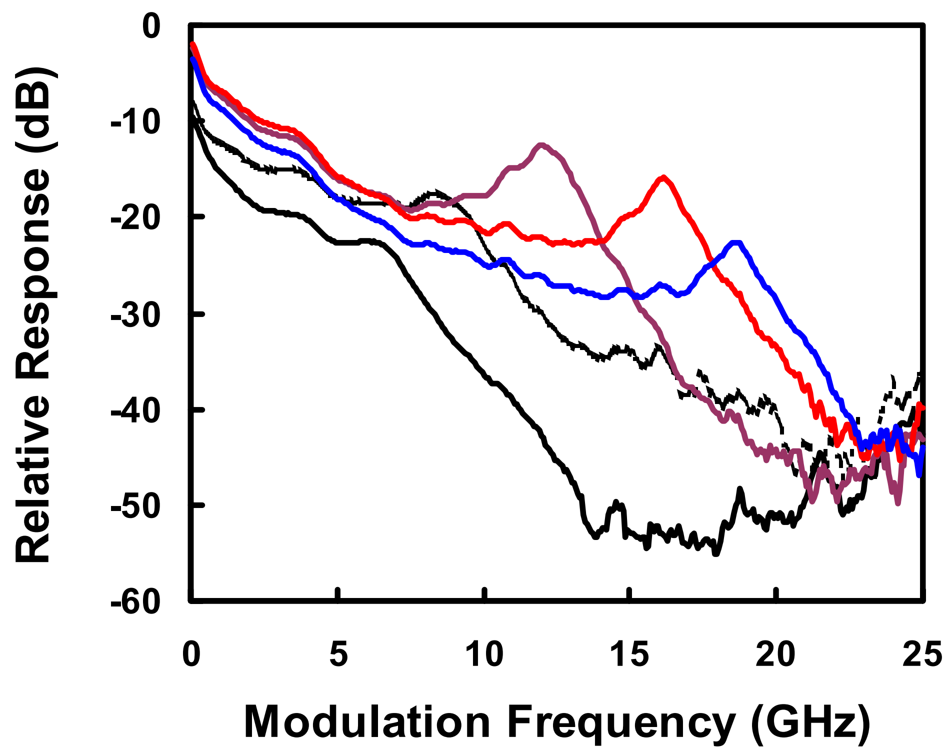
Modulation Dynamics of Directly Modulated DFB Laser with Strong Optical Injection



- **Enhance modulation bandwidth**
  - *Relaxation oscillation frequency* increased by 4 times
- **Resonant peak height controlled by detuning frequency**

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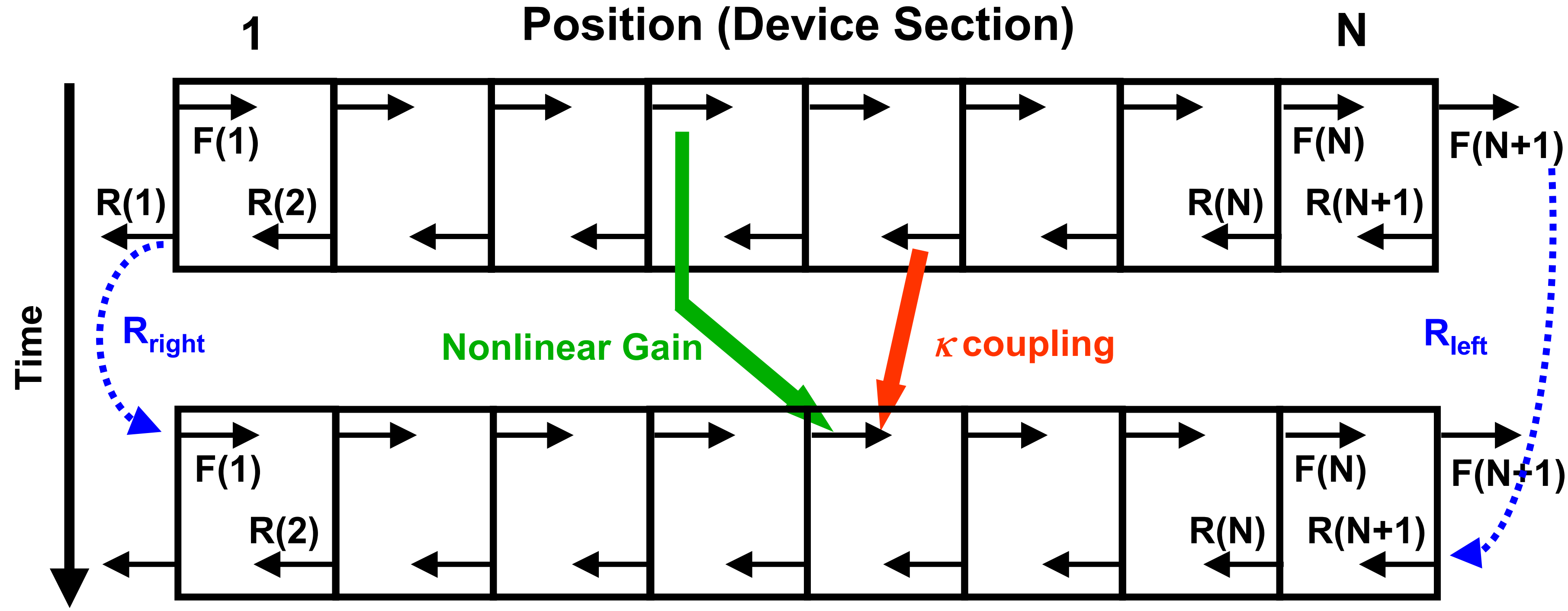
FDTD Modeling of DFB Lasers



Coupled Traveling Wave Equations

$$\frac{1}{c_g}\frac{\partial F}{\partial t}+\frac{\partial F}{\partial z}=(g-\alpha_L-i\delta)F+i\kappa R \qquad \frac{1}{c_g}\frac{\partial R}{\partial t}-\frac{\partial R}{\partial z}=(g-\alpha_L-i\delta)R+i\kappa F$$

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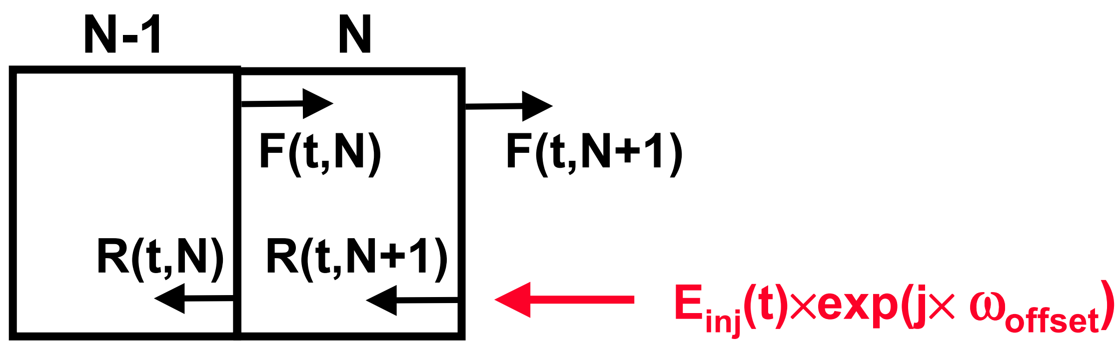
Modeling Optical Injection Locking Using FDTD Model

Modified Boundary Conditions



Injection Ratio:

$$\eta = E_{inj} / F(N+1)\ \text{(free-running)}$$

Boundary Conditions:

$$R(t+1,N) = F(t,N+1)\times R_{right}$$

Boundary Conditions with Optical Injection:

$$R(t+1,n+1) = F(t,n+1)\times R_{right} + E_{inj}(t)\exp(j\omega_{offset})$$

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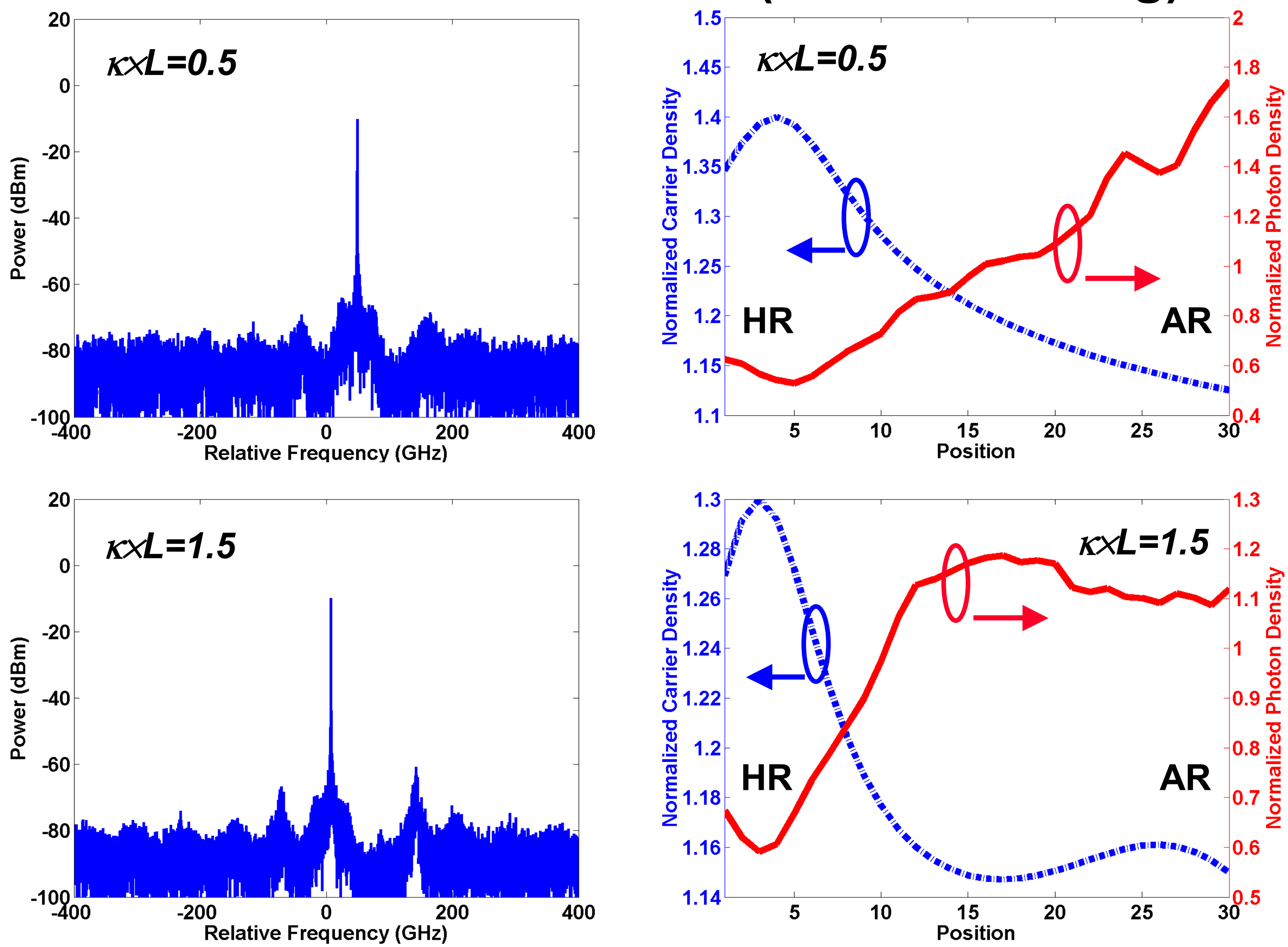
Advantages of FDTD Modeling of DFB Lasers and Optical Devices

- Accurately models the non-uniformities in the device
  - Spatial Hole Burning (SHB)
  - Non-uniform current injection (Split Contact Modulation Techniques)
- Models the cavity effects
  - Device characteristics for different $\kappa \times L$ products and facet reflectivities
  - Complex coupled DFB lasers can be modeled
- Multimode model
  - Takes into account other cavity modes and predicts side-mode suppression
- Model integrated photonic devices
  - EML residual reflections at the interfaces

Simulated Optical Spectrum of DFB Laser for Various $\kappa \times L$ Products (HR-AR Coating)



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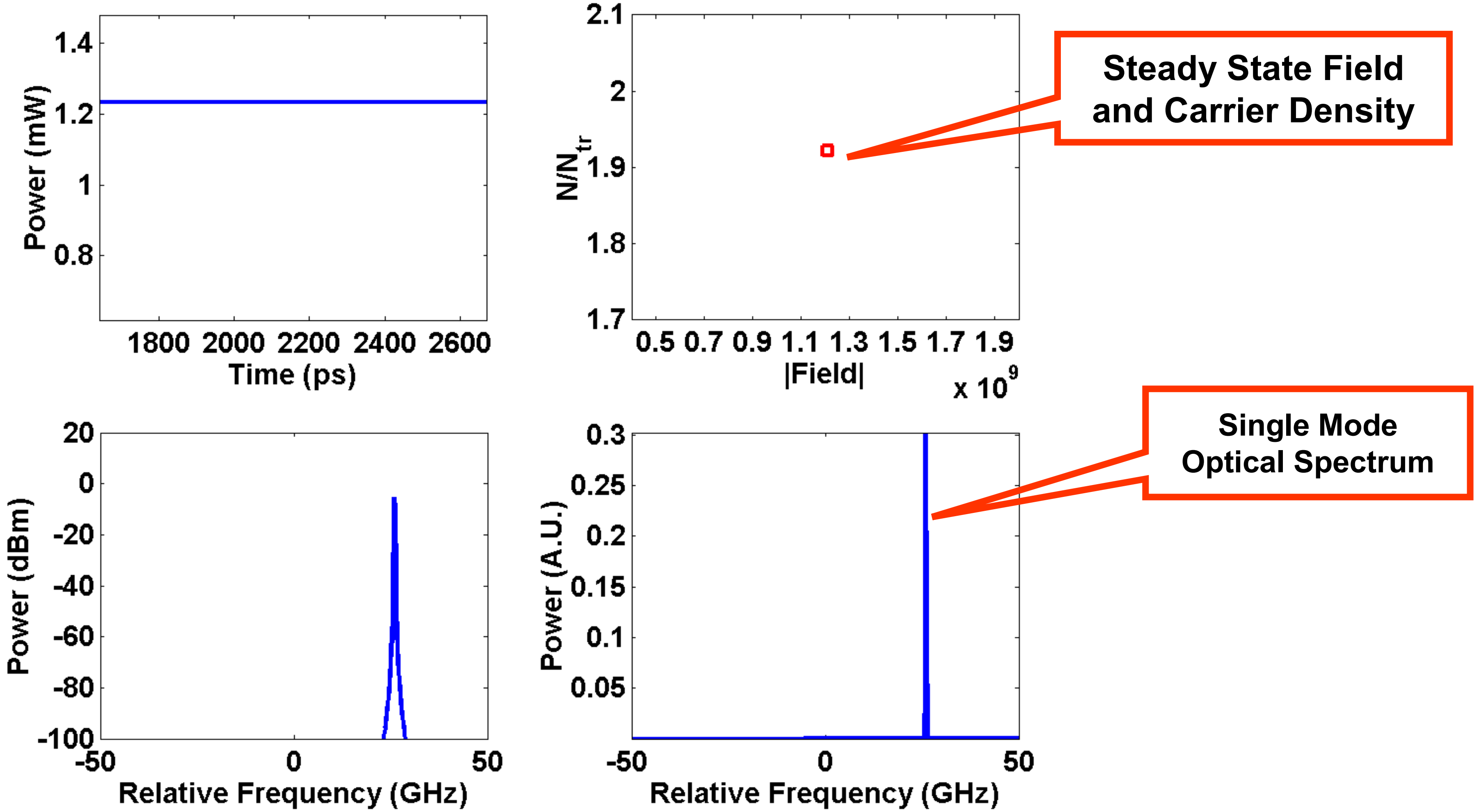
Stable Injection Locking Laser Dynamics



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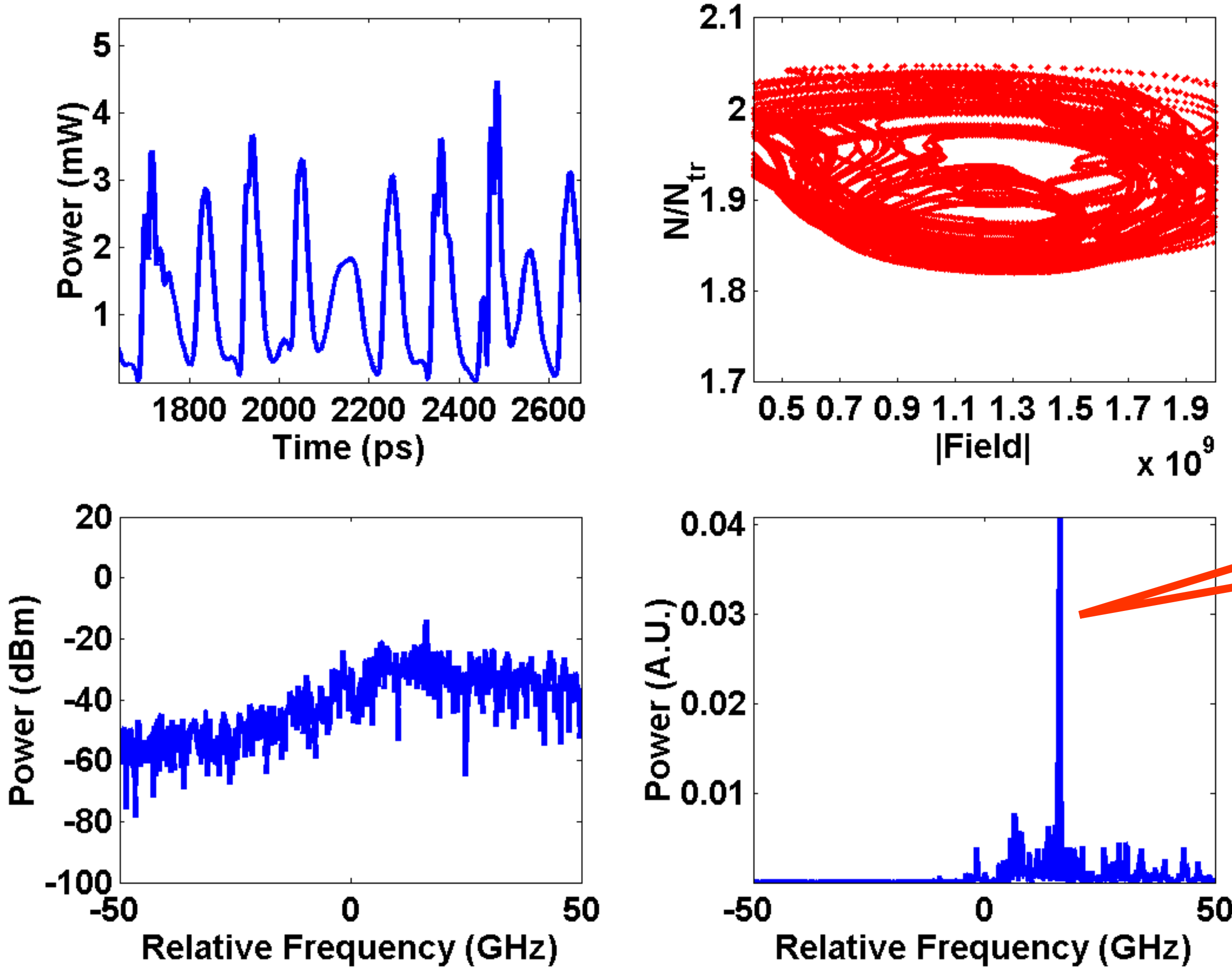
Chaotic Laser Dynamics Caused by Optical Injection



Highly Chaotic State

Broadband Optical Spectrum (Noise)

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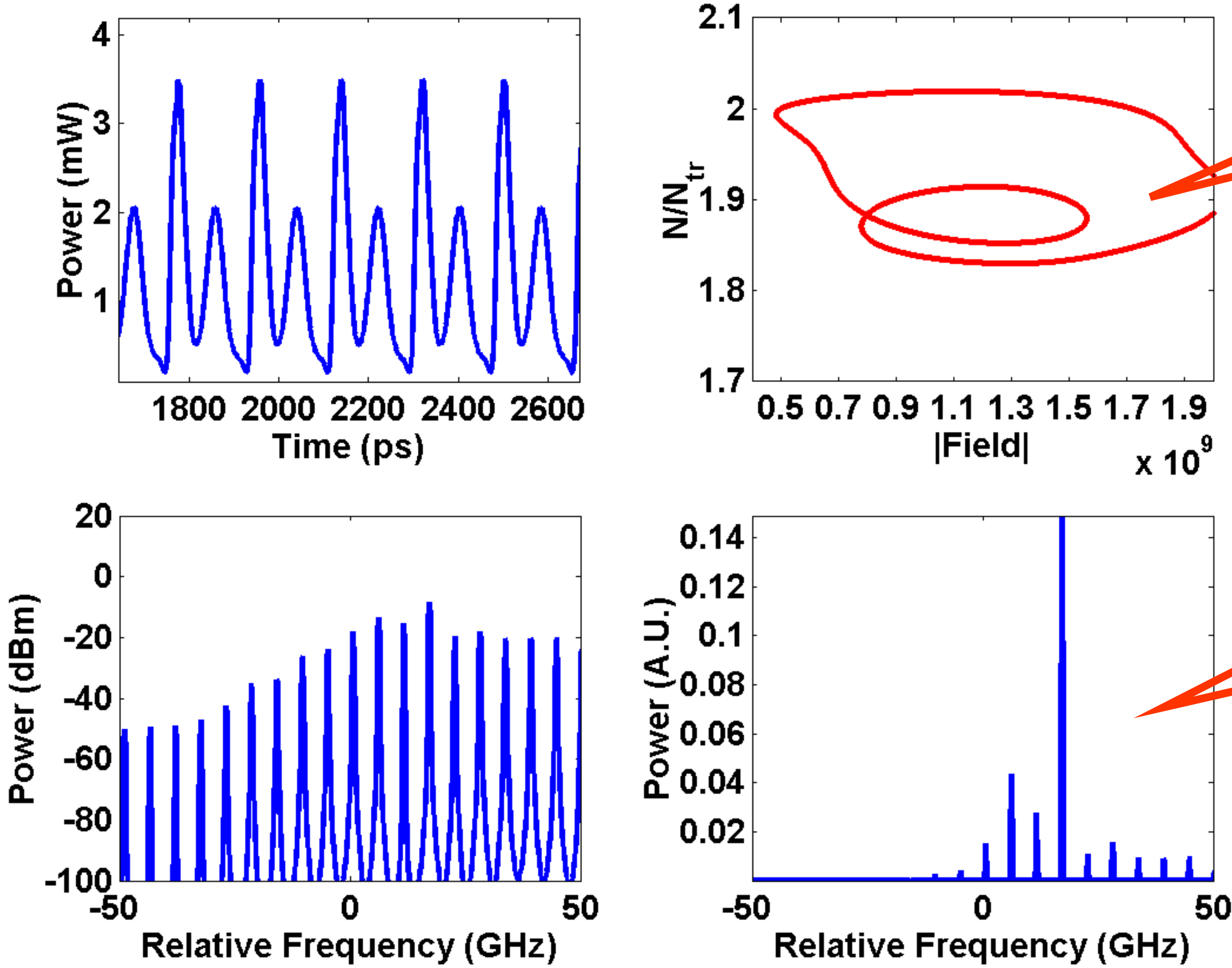
Periodic Optical Mixing in Semiconductor Lasers (Limit Cvcle)



Many possible states but predictable

Discrete Optical Frequency Spectrum (Mixing)

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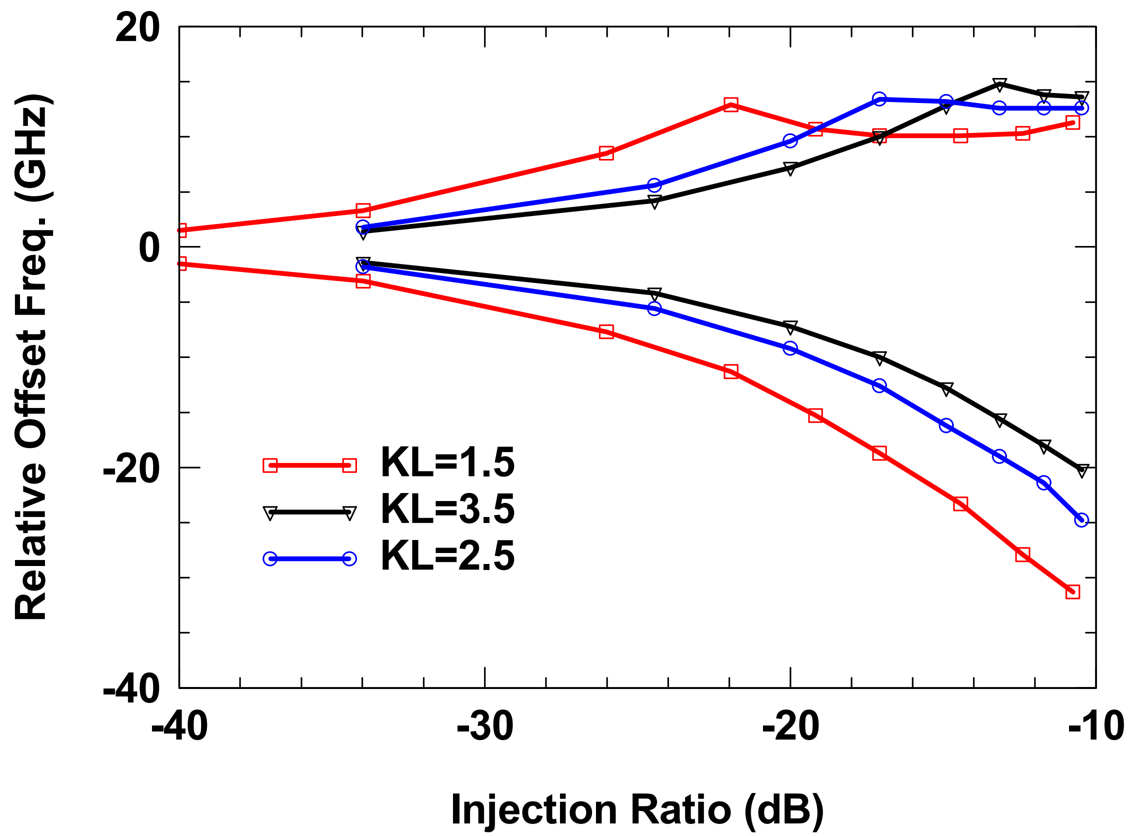
Simulated Locking Range for Various Various $\kappa \times L$ Products



- Locking range is symmetrical at low injection levels
- Size of stable locking range is a strong function of gain saturation

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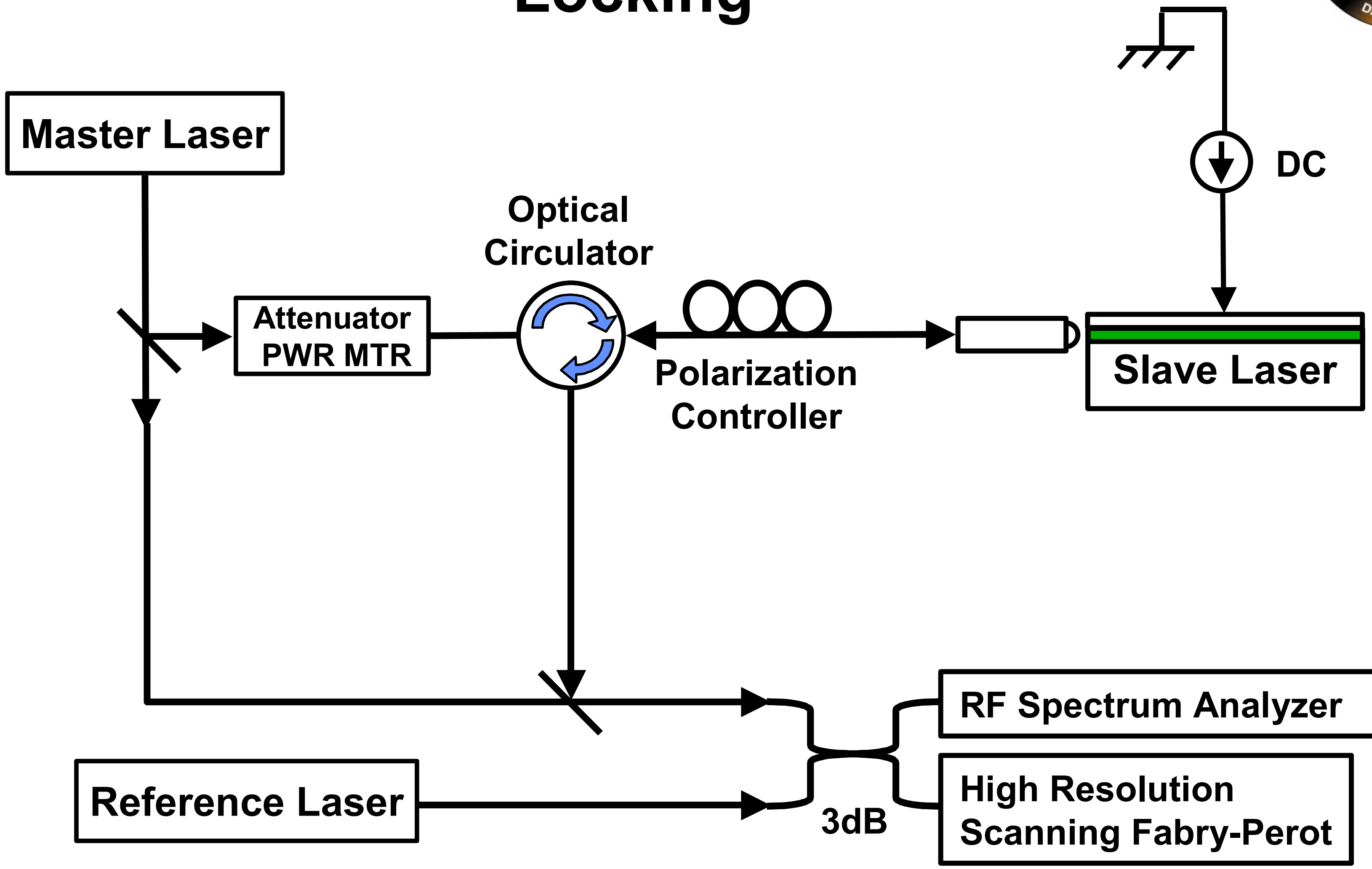
Experimental Set-up for Optical Injection Locking



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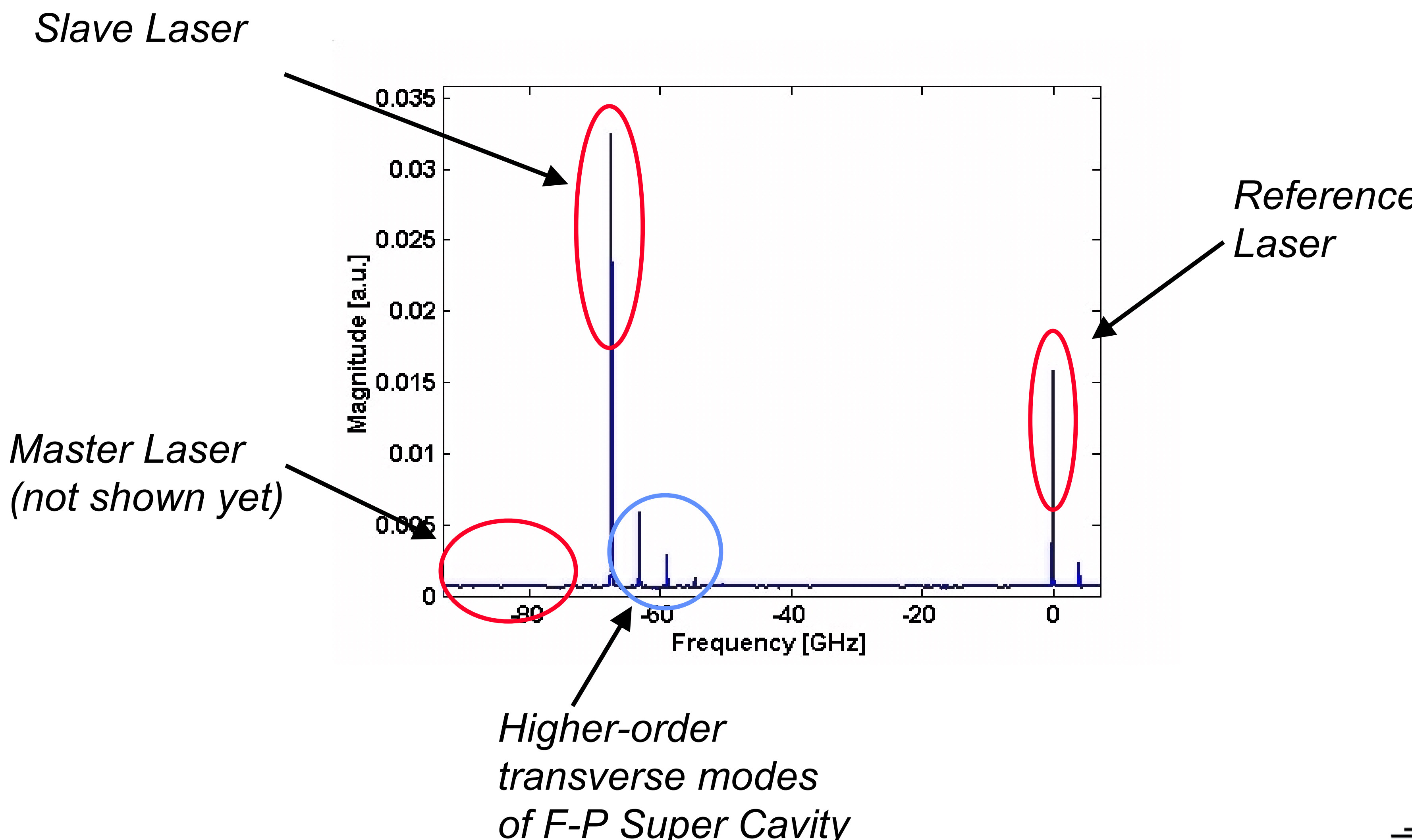
Injection Locking Visualization



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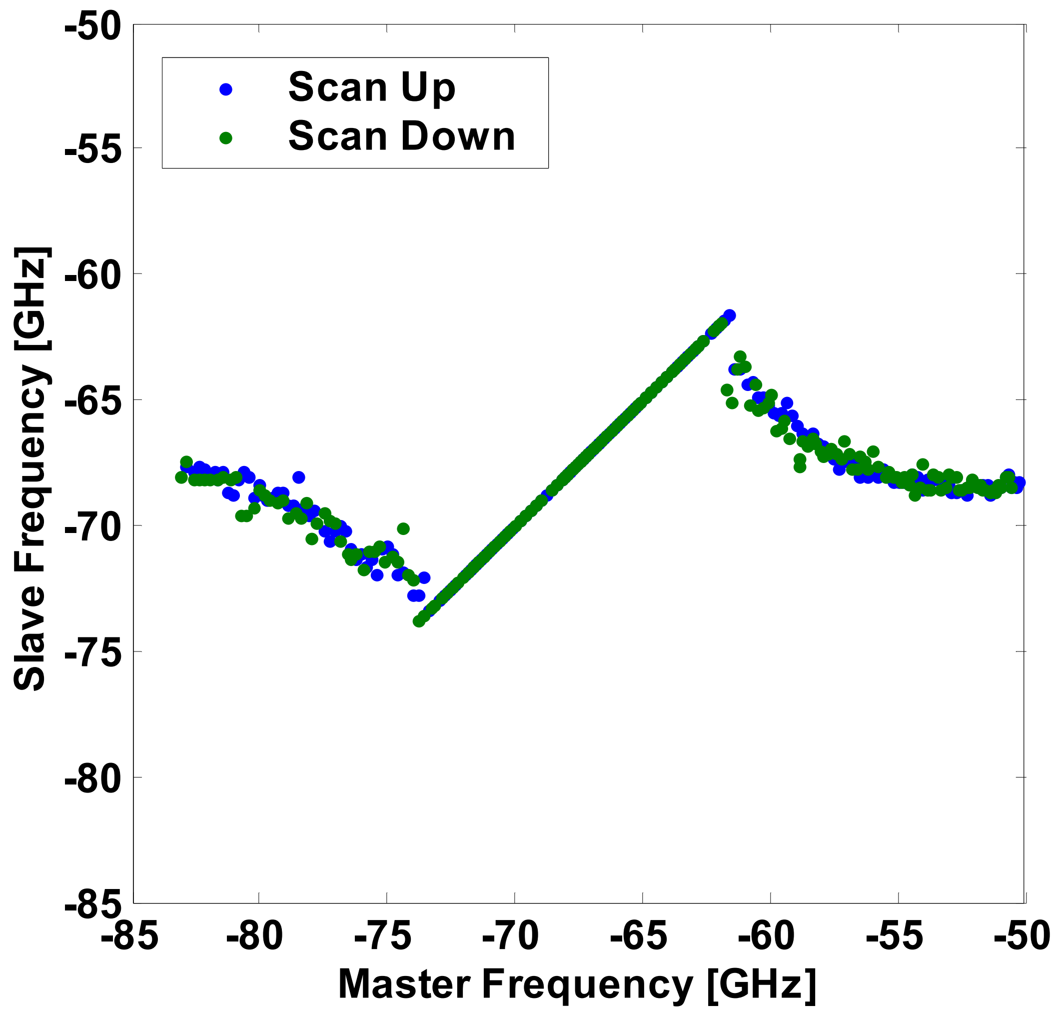
Locking Range



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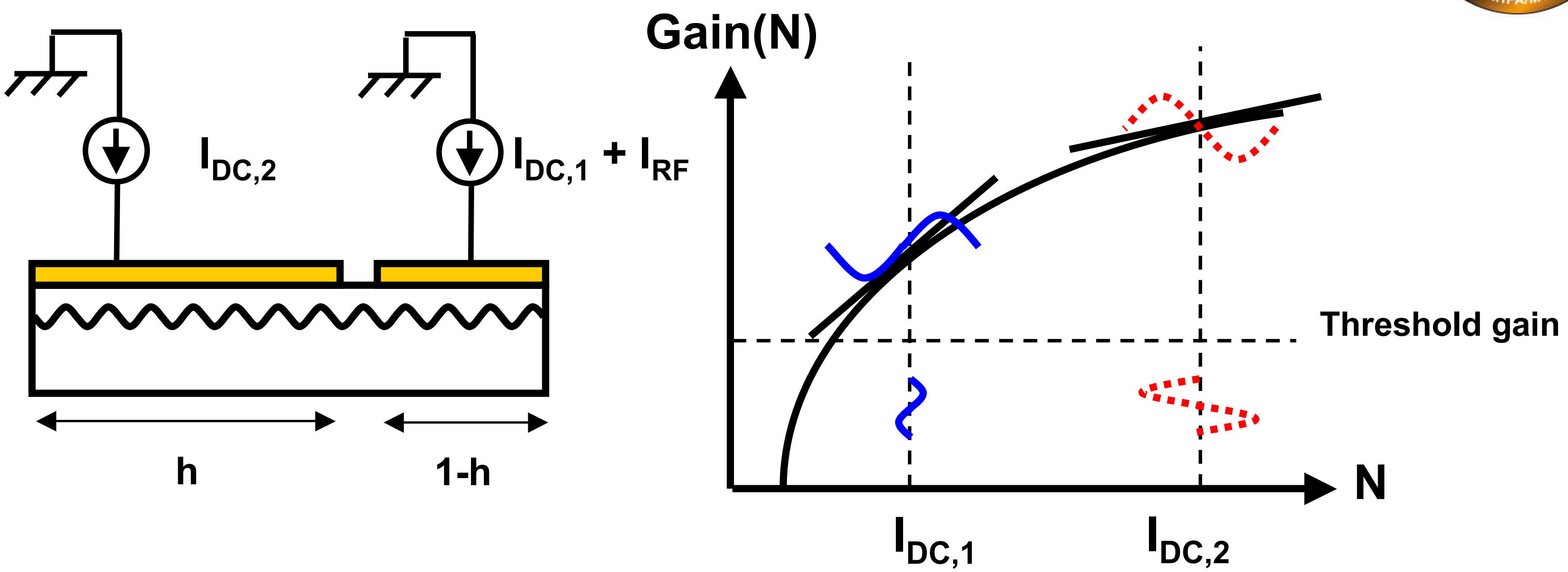
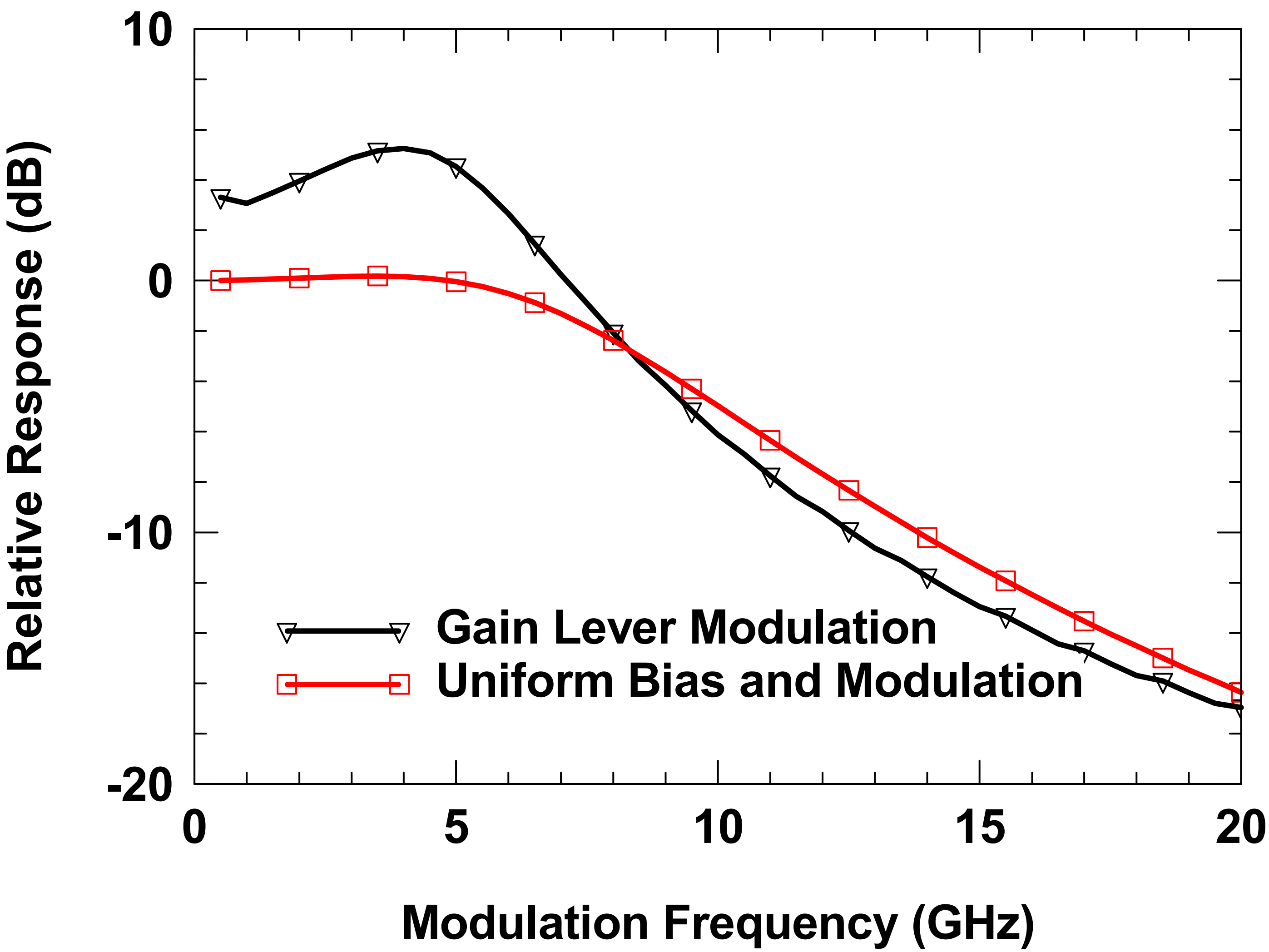
Gain Lever Modulation Using Semiconductor Lasers



- First demonstrated by Dr. Kam Lau ('89) using FP lasers
- Lasing Condition:
  Total Gain = Gain in Section 1 + Gain in Section 2 = Constant
  - Fabry-Perot laser model, uniform photon and carrier density
  - Lumped element model adequate
- Distributed Feedback Lasers
  - Non-uniform gain due to grating feedback (SHB)
  - Distributed model needed for detailed study

Simulated Gain Lever Modulation Response (Preliminary Results)



Conclusion

- Established a large-signal time-domain model for traveling-wave EAM
- Developed a comprehensive FDTD model for directly modulated DFB laser that is capable of simulating
  - Strong optical injection locking
  - Split-contact modulation
  - Non-uniform photon and carrier distribution in DFB
    - Spatial hole burning, gain saturation, AR-HR coating
  - Nonlinear distortion
  - RIN
- Established an automated experimental testbed for characterizing injection-locked lasers
  - Enable us to investigate detailed locking behavior over a wide range of parameter space